WASTE TO RESOURCES



Unlocking Potential Applications of Agricultural Waste

Edited by
Arup Giri, Rajesh Kumar, Sanju Bala Dhull, and Somen Acharya

Waste to Resources

Unlocking Potential Applications of Agricultural Waste

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Contents

List of Contributors ix
Preface xiii
Foreword xv

Part I
Understanding agricultural and food wastes

1. Beyond the harvest: The origins and diversity of crop residues and byproducts

Siril Singh, Rajni Yadav, and Anand Narain Singh

1.1. Introduction 3
1.2. Origin and composition 4
1.3. Diverse forms of crop residues 5
1.4. Byproducts of processing 8
1.5. Utilization and benefits 10
1.6. Challenges and opportunities 11
1.7. Conclusion and recommendation 12
References 13

2. Livestock waste: Sources, types, and composition

Sreekumar Damodaran Nair, Anshul Gautam, Narayanan Sajeev Beena, and Muskan Kaushal

2.1. Introduction 21
2.2. Livestock production 22
2.3. Production of livestock wastes 22
2.4. Livestock wastes and environment 27
2.5. Environmental impact reduction 28
2.6. Odors associated with livestock wastes 29
2.7. Pathogens in livestock wastes 30
2.8. Livestock waste utilization 31
2.9. Conclusion 33
References 33

3. Pesticide and chemical waste: Exploring the sources, composition, and characteristics

Dimple Parashar, Ruby Dahiya, Sonu Saini, and Arup Giri

3.1. Introduction 37
3.2. Occurrence, distribution, and possible sources of agricultural pesticide 38
3.3. Nano-pesticides and nano-fertilizers from natural (plant/animal) wastes 39
3.4. Occurrence, distribution, and possible sources of agricultural chemicals 40
3.5. Environmental impact and ecological consequences of pesticide and chemical waste 40
3.6. Technological advances in pesticide and waste management 43
3.7. Conclusion 44
References 45

4. Nutrient, fertilizer, and plastic waste in the agriculture sector

Bibhash Chandra Verma, Soumya Saha, Nandini Roy, Debarati Bhaduri, Priyamedha, Amrita Banerjee, and Somnath Roy

4.1. Introduction 49
4.2. Current scenario of fertilizer and plastic use in agriculture 50
4.3. Waste and its classification 51
4.4. Nutrient, fertilizer, and plastic waste 52
4.5. Waste to wealth 57
4.6. The prospect of agricultural waste management 58
4.7. Conclusions 58
References 58

5. Food processing waste: Understanding the sources, composition, and characteristics

Ahmed Hamad and Islam Ibrahim Sabeq

5.1. Introduction 61
5.2. Source of food processing waste 62
5.3. Animal-derived processing waste (ABPs) 63
5.4. Food processing waste characterization 65
5.5. Food processing waste management and reduction 66
5.6. Food processing waste recycling 66
5.7. Valorization of food processing waste 68
5.8. Conclusion 73
References 74

6. Water footprints of the global agriculture sector

Ruby Dahiya, Dimple Parashar, and Arup Giri

6.1. Introduction 79
6.2. The global value of water in agriculture 80
6.3. Ecological footprints and agriculture 81
6.4. Water scarcity in agriculture: Causes, impacts, and mitigation 82
6.5. Understanding water footprints: Definitions and components 83
6.6. Water footprint of global food production 84
6.7. Water footprint for specific agricultural productions with energy purposes 85
6.8. Assessing water footprints: Methodologies and tools 86
6.9. Factors affecting water footprint 90
6.10. Decreasing water footprints through precision agriculture 92
6.11. Conclusion 93
References 94

Part II
Environmental impact and ecological considerations

7. The ecological footprint of agricultural waste: Pollution and greenhouse gas

Hend A. Hamed, Marwa T. El-Mahdy, Mona F.A. Dawood, Marwa Hindawy, and Adel R.A. Usman

7.1. Introduction 101
7.2. Comparative analysis of agricultural practices 102
7.3. Agriculture waste pollution: Measurement and impact 104
7.4. Greenhouse gas emissions in agriculture: Sources and dynamics 106
7.5. Methodologies for ecological footprint calculation 111
7.6. Technological innovations in shaping ecological footprint reduction 112
7.7. Challenges and future considerations 113
7.8. Conclusion and recommendations 116
Acknowledgment 117
References 117

8. Emissions from fertile to fragile: Understanding soil degradation and erosion due to agricultural waste

Naveen Jose, Pramod Shelake, Shilpa S. Selvan, and Manisha Jagadale

8.1. Introduction 121
8.2. Impact of agricultural activities on soil health 123
8.3. Significance of addressing agricultural waste in soil conservation 123
8.4. Impact of agricultural waste on soil health 124
8.5. Strategies for managing agricultural waste 124
8.6. Understanding agriculture waste as a resource 125
8.7. Environmental impact of agricultural waste accumulation 126
8.8. Strategies for mitigating agricultural waste and soil degradation 128
8.9. Emerging trends in agricultural waste management 130
8.10. Conclusion 131
References 131

9. Pyrethroids contamination: Understanding the impacts on freshwater invertebrates and fish

Rajib Majumder

9.1. Introduction 137
9.2. Evolution of pyrethroids generations 138
9.3. Uses of pyrethroids 138
9.4. Mode of actions 138
9.5. Transport, persistence, and bioavailability in water 139
9.6. Effects on freshwater invertebrates 140
9.7. Effects on tadpoles of Amphibia 143
9.8. Effects on freshwater fish 143
9.9. Future research scopes 148
9.10. Conclusion 148
References 148

10. The ecological toll: Biodiversity loss and habitat degradation caused by agricultural waste

Suresh Kumar, Divya, Shivani Thakur, and Rajesh Kumar

10.1. Introduction 155
10.2. Various sources of agricultural waste 156
10.3. Impact of agricultural waste on ecosystem 160
10.4. Soil faunal diversity and soil degradation 162
10.5. Impact of agricultural residue burning on biodiversity 162
10.6. Impact of agriculture waste on greenhouse gas emission 163
10.7. Policy implications and knowledge gaps 163
10.8. Sustainable approaches for agricultural waste management 163
10.9. Conclusion 164
Acknowledgments 164
References 164

11. The hidden dangers: Agricultural waste and its impact on human health

Subramani Srinivasan

11.1. Introduction 167
11.2. Agricultural wastes 168
11.4. Environmental impact of agro-wastes 171
11.5. Impact of agricultural waste exposure on human health 172
11.6. Conclusion 176
References 176

Part III
Waste management technologies for waste mitigation

12. Traditional and modern waste management technologies: Challenges and limitations

Christopher Muyiwa Aboyeji, Faith Oluwatobi Okunlola, and Wanger Barnabas Akaazua

12.1. Introduction 183
12.2. Overview of traditional agricultural waste management techniques 184
12.3. Evolution of modern agricultural waste management technologies 188
12.4. Critical challenges in traditional agricultural waste management 190
12.5. Limitations of modern agricultural waste management technologies 192
12.6. Integration of traditional and modern approaches 195
12.7. Technological innovations in agricultural waste management 197
12.8. Conclusion 198
AI Disclosure 198
References 199

13. Integrated waste management systems: Holistic approaches to waste management in agriculture

Rajesh Kumar, Younis Hajam, and Seema Rai

13.1. Introduction 203
13.2. Importance of integrated waste management systems (IWMS) 204
13.3. Environmental and economic impacts of agricultural waste 205
13.4. Biological treatment methods 206
13.5. Chemical treatment methods 207
13.6. Combined and integrated approaches 208
13.7. Chemical precipitation 210
13.8. Physical treatment methods 211
13.9. Conclusion 212
References 213

14. Anaerobic digestion of waste for sustainable energy production: Principles, applications, and sustainable challenges

Djaber Tazdaït, Rym Salah Tazdaït, and Abdenour Ait Ouazzou

14.1. Introduction 215
14.2. Types of waste from the industrial and agricultural sectors 217
14.3. Bioremediation 218
14.4. Valorization of waste through microbial decomposition 218
14.5. Biofuel production through waste digestion 220
14.6. Methane production coupled with waste biodegradation 221
14.7. Challenges and perspectives of waste energetic valorization 224
14.8. Conclusion 226
References 226

15. Waste-to-energy technologies: Harnessing biogas from agricultural waste

Luis Fernando Flores, Brenda Juana Flores, Carlos Saul Osorio Gonzalez, Rahul Saini, and Satinder Kaur Brar

15.1. Introduction 231
15.2. Biochemical conversion 232
15.3. Anaerobic digestion biogas production process 233
15.4. Pretreatment of agricultural waste biomass for biogas production 234
15.5. Operational methods and reactor designs 238
15.6. Factors affecting biogas production 239
15.7. Additives to enhance biogas production from agricultural wastes 241
15.8. Biogas upgrading 241
15.9. Biogas applications 244
15.10. Global overview of biogas production 245
15.11. Biogas benefits and limitations 246
15.12. Future perspectives 248
15.13. Conclusion 249
References 249

16. Industrial applications of agricultural waste for value-added products

Sahil Kapoor, Meenakshi Singh, and Piyush Choudhary

16.1. Introduction 253
16.2. Conversion of agro-waste into environmentally benign industrial products 254
16.3. Achieving SDGs through agro-waste innovations 257
16.4. Assessment of the bioenergy potential of agriculture waste 258
16.5. Conclusion 261
Acknowledgment 261
References 261

17. Nanotechnology and agro-industrial wastes as a sustainable and future approach in agricultural applications

Juliana Botelho Moreira, Suelen Goettems Kuntzler, Priscilla Quenia Muniz Bezerra, Ana Claudia Araujo de Almeida, Danielle Rubim Lopes, Jorge Alberto Vieira Costa, and Michele Greque de Morais

17.1. Introduction 267
17.2. Nanotechnology applied in agriculture 268
17.3. Strategies for nanoparticles production 270
17.4. Agricultural wastes as a source of materials for NPs 271
17.5. Potentiality of nanoparticles in agriculture 272
17.6. Mechanism of action of the nanoparticles 274
17.7. Challenges 275
17.8. Conclusion and future perspectives 275
Acknowledgments 276
References 276

Part IV
Waste valorisation and resource utilisation

18. Nutrient recovery and recycling: Extracting and reusing nutrients from agricultural waste

Argha Chakraborty, Shibasis Mukherjee, Sudipta Tripathi, Krishnendu Ray, and Gautam Chatterjee

18.1. Introduction 283
18.2. Agricultural waste as a nutrient source 285
18.3. Nutrient extraction techniques 288
18.4. Nutrient recovery technologies 290
18.5. Applications 294
18.6. Challenges and barriers 296
18.7. Conclusion and future perspectives 297
References 297

19. Transforming waste into worth: Exploring value-added products from agricultural waste

Jahidul Hassan, Yukio Ozaki, Joydeb Gomasta, Liakat Ali, and Syada Nizer Sultana

19.1. Introduction 307
19.2. Agricultural contribution in food and environment 308
19.3. Sources and characteristics of agricultural waste 310
19.4. Management and utilization of agricultural waste 313
19.5. Strategies for conversion of waste to wealth 317
19.6. Agricultural waste generated value-added products in relation to SDGs 318
19.7. Future potential of bioconversion of agricultural waste using biotechnologies 321
19.8. Challenges and future research directions 324
19.9. Conclusions 325
References 325

20. Agricultural waste as a renewable resource: Biomass and biofuel production

Limin Yang and Qian Lu

20.1. Introduction 333
20.2. Agricultural waste and environmental pollution 334
20.3. Valorization of agricultural waste by microalgae cultivation 335
20.4. Solid-state fermentation of crop waste by high-value microorganisms 339
20.5. Production of hydrogen gas by using agricultural waste 341
20.6. Assessment of the greenhouse gas emission 342
20.7. Conclusion and future prospects 344
References 345

21. Vermicomposting for waste decomposition and soil health improvement: Risk and challenges

Binaya Kumar Pattnaik, Rasmita Behera, Praful NK, and Debojyoti Moulick

21.1. Introduction 349
21.2. Vermicomposting process 351
21.3. Benefits of vermicomposting 357
21.4. Risks associated with vermicomposting 358
21.5. Challenges in vermicomposting 360
21.6. Economic considerations 362
21.7. Strategies for mitigating risks and overcoming challenges 363
21.8. Future directions and opportunities 365
21.9. Conclusion 367
References 367

22. Residue to rations: Enhancing livestock nutrition with agricultural byproducts

Maria Papageorgiou, Agori Karageorgou, Michael Goliomytis, Ouranios Tzamaloukas, and Panagiotis Simitzis

22.1. Introduction 375
22.2. Application of agro-industrial byproducts in animal diets 376
22.3. Potential limitations of utilizing agro-industrial byproducts in animal nutrition and future perspectives 398
22.4. Conclusions 402
References 402

23. Biochar production: Utilizing waste for carbon sequestration and soil improvement

Biraj Bandhu Basak, Abhijit Sarkar, Ajoy Saha, Rohan Sarkar, Shrila Das, and Jyotirmay Roy

23.1. Introduction 415
23.2. Biochar production from waste 416
23.3. Biochar properties 418
23.4. Biochar induced carbon sequestration 420
23.5. Biochar-induced soil improvement 421
23.6. Conclusion 425
References 426

24. Sustainable solutions: Utilizing agricultural waste for bioplastics and biofibers

Rabab M. Nasser

24.1. Introduction 431
24.2. Agricultural waste: An untapped resource 432
24.3. Potential of agricultural waste for bioplastics and biofibers 432
24.4. Chemical conversion mechanisms for transforming agricultural wastes into bioplastics and biofibers 434

24.5. Challenges and limitations 435
24.6. Cost and scalability 436
24.7. Environmental impact assessment 437
24.8. Solutions and ongoing research efforts 437
24.9. Conclusion 438
References 438

25. Waste not, mushroom lots: Innovative cultivation methods with agricultural residues

Sindhu Rajashekar, Thanmaya Murthy, Kiran Moganna, Supreeth Mohan Kumar, and Manasa Ravindra Walmiki

25.1. Introduction 443
25.2. Biology of mushroom cultivation and mushroom types 444
25.3. Agro-waste substrates and their impact on mushroom growth 451
25.4. Innovations, smart farming technologies, and automated cultivation processes in mushroom cultivation 453
25.5. Agro-repurposing of spent mushroom substrate (SMS) in sustainable agronomic practices 455
25.6. Conclusions 461
Acknowledgments 461
References 461

Part V
Regulatory and policy frameworks for sustainable waste management

26. Policies and strategies to promote sustainable agricultural waste management practices

Ruby Dahiya, Dimple Parashar, Arup Giri, Rajesh Kumar, and Somen Acharya

26.1. Introduction 467
26.2. Strategies for promoting sustainable agricultural waste management 468
26.3. Approaches for integrated waste management 470
26.4. Case studies and best practices 472
26.5. Policies and regulatory framework 472
26.6. Conclusion 474
References 474

27. Emerging trends and future prospects in agricultural waste management

Kirpa Ram, Sunder Singh Arya, Navneet Kumari, and Chanchal Garg

27.1. Introduction 477
27.2. Types and sources of agriculture waste 478
27.3. Environmental and economic impacts of unmanaged waste 480
27.4. Sustainable waste management strategies 483
27.5. Challenges in agriculture waste management 486
27.6. Innovative technologies and approaches 487
27.7. Future directions and research opportunities 487
27.8. Summary and conclusion 488
AI disclosure 488
References 489

28. Potential agricultural waste management practices to contribute to a sustainable and circular agricultural system

Rahul Gogoi, Amarjeet Singh Bhogal, Priyadarshini Deka, Jitul Bora, Jugabrata Das, and Sudipta Sankar Bora

28.1. Introduction 493
28.2. The potential of agricultural wastes in the circular economy 494
28.3. Potential of microbial biotechnology in agro-waste management 501
28.4. Valorization of agro-waste for livestock welfare 506
28.5. Challenges and opportunities 507
28.6. Conclusion 507
References 507

Index 513

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Preface

Agriculture contributes toward the food and nutritional security and the economic growth of a country; improper management of agricultural waste generated and accumulated in the process poses significant environmental challenges. In an era when resource efficiency and sustainability have become global imperatives, it is increasingly evident that agricultural waste should no longer be viewed as a mere disposal issue but as a valuable resource with untapped potential. This realization has driven the creation of *Waste to Resources: Unlocking Potential Applications of Agricultural Waste,* a volume designed to offer a comprehensive exploration of how agricultural waste can be transformed into valuable resources.

The book's inception stemmed from a critical need to address the environmental impact of agricultural practices while simultaneously uncovering innovative approaches to waste management. As editors, we envisioned a resource that would connect the dots between the problems associated with agricultural waste and the enormous potential that arises from transforming waste into resources. Through this book, we aim to provide readers with a deep understanding of agricultural waste, along with practical techniques, real-world examples, and forward-looking perspectives on sustainable solutions.

The chapters presented in this volume are the result of collaboration among experts from diverse fields, ranging from agriculture and environmental science to policy and engineering. Together, they offer an interdisciplinary perspective of the composition, environmental impact, and management of agricultural waste. In addition, this book delves into emerging technologies and innovative practices that have the potential to revolutionize waste management strategies in agriculture, such as bioenergy production, nutrient recycling, and the creation of bio-based materials.

One of the key elements of the book is its focus on the practical implementation and innovative approaches and to explore new strategies for waste management. This volume emphasizes step-by-step guidance on a variety of techniques, including composting, anaerobic digestion, and recycling, all tailored to the unique needs of the agricultural sector. Furthermore, the book examines the broader regulatory and policy frameworks, offering readers insights into the legislative landscape that governs waste management and its future direction.

Our goal with this book is twofold. First, we seek to equip readers with a solid foundation in understanding agricultural waste and its broader implications for the environment, resource use, and sustainability. Second, we aim to empower them with the knowledge and tools to embrace innovative waste management practices that can not only mitigate environmental harm but also unlock new economic opportunities.

We hope that *Waste to Resources: Unlocking Potential Applications of Agricultural Waste* will serve as a valuable reference for academics, researchers, practitioners, policymakers, and students alike. It is our sincere belief that the insights and strategies outlined in this volume will foster a more sustainable and resource-efficient future, not only for the agricultural sector but for society as a whole.

As the editors, we extend our deepest gratitude to the authors for their thoughtful ideas, valuable contribution, dedication, and expertise. The editors are grateful to Elsevier for supporting this project and to all the staff of Elsevier involved in this project for all the cooperation extended. We are confident that this book will inspire new perspectives on agricultural waste management and contribute meaningfully to ongoing efforts toward environmental sustainability.

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Foreword

In an era when environmental sustainability and resource management are paramount concerns, it is with great pleasure that I introduce this timely and insightful volume, *Waste to Resources: Unlocking Potential Applications of Agricultural Waste*. Edited by Dr. Arup Giri, Dr. Rajesh Kumar, Dr. Sanju Bala Dhull, and Dr. Somen Acharya, this book addresses one of the most pressing issues of our time—how to effectively manage and utilize agricultural waste for the betterment of society and the environment.

Agriculture, being the backbone of many economies, generates substantial amounts of waste that, if left unmanaged, can have significant environmental consequences. Yet, as this book eloquently demonstrates, agricultural waste is not merely a byproduct to be discarded. It is a resource with immense untapped potential, one that, when properly harnessed, can contribute to sustainable development, renewable energy, and improved ecosystem health.

The editors of this volume have meticulously compiled a wealth of knowledge, bringing together scientific insights, case studies, and practical solutions within 28 chapters written by famous authors across the world. This holistic approach offers readers a comprehensive understanding of agricultural waste, ranging from its composition and sources to innovative waste management techniques. Moreover, the emphasis on policy and regulatory frameworks provides a roadmap for creating a more resilient and sustainable agricultural sector.

Particularly noteworthy are the innovative waste management strategies discussed in the book, such as bioenergy production, nutrient recycling, and the creation of bio-based materials. These techniques not only reduce environmental impact but also unlock economic opportunities, demonstrating the transformative potential of agricultural waste.

In an increasingly resource-constrained world, this volume serves as a beacon for researchers, policy-makers, and practitioners alike. It offers practical solutions while inspiring a broader dialogue on the future of agricultural sustainability. By exploring the intricate relationship between waste and resource efficiency, this book empowers readers to turn challenges into opportunities, paving the way for a greener and more resilient agricultural industry.

I commend the editors and contributors for their outstanding efforts in producing this comprehensive resource. It is my firm belief that *Waste to Resources* will become an essential reference for those seeking to navigate the complexities of agricultural waste management and its potential applications.

I am confident that this book will inspire meaningful action, fostering innovation and driving the global agricultural sector toward a more sustainable and resource-efficient future. I greatly appreciate the efforts put in by the editors for successfully bringing together this impressive volume.

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Part I

Understanding agricultural and food wastes

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Chapter 1

Beyond the harvest: The origins and diversity of crop residues and byproducts

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Chapter Outline

1.1. Introduction 3
1.2. Origin and composition 4
1.3. Diverse forms of crop residues 5
1.4. Byproducts of processing 8
1.5. Utilization and benefits 10
1.6. Challenges and opportunities 11
1.7. Conclusion and recommendation 12
References 13

1.1 Introduction

The growing demand for food due to population expansion and improved breeding techniques has led to a sharp rise in crop production around the world (Lenaerts, Collard, and Demont, 2019). The multitude of agricultural activities has amplified the generation of crop residue and its byproducts globally. Crop residues and byproducts comprise a wide range of materials derived from agricultural activities, including crop production, processing, and post-harvest handling (Shinde *et al.*, 2022). Some researchers define it as "remains that are generated from crop-packing plants or that are discarded during crop processing." The very famous quote of Smil (1999) says, "Crop residues should be seen not as wastes but as providers of essential environmental services, assuring the perpetuation of productive agroecosystems." The fibrous crop biomass left after harvesting more valuable parts is considered crop residue and is often treated as the noneconomic part of crop production. Kumar *et al.* (2023) describe it as a rich source of plant nutrients, having the potential to improve resource use efficiency along with the sustainability of the agroecosystem. Some researchers have classified crop residues into two kinds: field residues and process residues (Ali *et al.*, 2019). Field residues are the materials left in plantation areas after harvesting the crop. These residues include stalks, stems, seed pods, and leaves. With proper management of these residues, the efficiency of irrigation and control of erosion can be accomplished effectively. Once the crop is processed into a usable resource, the leftover materials are called process residues (Ali *et al.*, 2019; Zhu *et al.*, 2023). Generally, these residues include bagasse, husks, seeds, roots, and molasses. These residues can be used as animal fodder and fertilizers for soil improvement.

Crop residue and byproducts play a crucial role in the agroecosystem, influencing soil health, carbon sequestration, and nutrient cycling (Maqsood *et al.*, 2022). Crop residue also acts as a good source of organic matter that conserves the carbon stock in soil, helps to maintain soil moisture, recycles nutrients, and reduces environmental hazards by lowering the amount of residue burning in fields (Prasad *et al.*, 2020). Depending on the soil fertility and crop species, after decomposition, crop residue contributes several major and minor mineral nutrients (Lal, 2005). The NPK potential of major crop residue-producing crops of the world along with their individual N, P_2O_5, and K_2O content in percent is given in Table 1.1.

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TABLE 1.1 Nutrient potential of different crop residues. Modified and adapted from (Shinde *et al.*, 2022)

Crop	N (%)	P_2O_5 (%)	K_2O (%)
Rice	0.61	0.18	1.38
Wheat	0.48	0.16	1.18
Pulses	1.29	0.36	1.64
Oilseed	0.80	0.21	0.93
Sugarcane	0.40	0.18	1.28
Maize	0.52	0.18	1.35
Soya bean	0.88	0.14	0.65
Potato	0.52	0.21	1.06

Modified and adapted from Shinde, R., Shahi, D.K., Mahapatra, P., Singh, C.S., Naik, S.K., Thombare, N., & Singh, A.K. (2022). Management of crop residues with special reference to the on-farm utilization methods: A review. Industrial Crops and Products, 181. https://doi.org/10.1016/j.indcrop.2022.114772

The types and quantities of residues vary significantly among different crops, impacting their management and utilization. Collecting and managing crop residues from the field is energy- and labor-intensive, and it takes time, causing adjournments in sowing the subsequent crop (Kumar *et al.*, 2023). As a result, farmers in many countries choose to burn these residues on-site, which leads to air pollution, hinders nutrient recycling, and negatively impacts soil microbes and beneficial fauna due to overheating and carbon loss (Hiloidhari, Das, and Baruah, 2014). Wheat and rice residues constitute the largest portion of crop residues burned in the field, significantly contributing to atmospheric pollution by emitting greenhouse gases such as carbon dioxide, carbon monoxide, methane, nitrogen oxides, and sulfur dioxide along with soot and particulate matter (Tokas *et al.*, 2021). To avoid the detrimental environmental effects of crop residue burning, it is vital to find efficient ways to utilize crop residues.

Crop residues and byproducts have historically been used to produce bedding material (Grimes, Smith, and Williams, 2002), livestock feed (Devi *et al.*, 2017), compost (Yadav *et al.*, 2023), biochar production (Nematian, Keske, and Ng'ombe, 2021), mushroom cultivation (Biswas and Layak, 2014), and so on. But, recently, researchers, farmers, and policy-makers have begun to view crop residue as a resource reservoir and have been coming up with creative ways to valorize it for the generation of value-added products. This includes the production of biofuels such as bioethanol, biomethane, biohydrogen, and biogas (Awogbemi and Kallon, 2023; Ali *et al.*, 2019), used in the packaging industry, baking industry, pharmaceutical industry, drug manufacturing, enzyme production, and energy generation, to name a few (Duan *et al.*, 2024; Tufail *et al.*, 2021; Bilo *et al.*, 2018).

These residues and byproducts can offer a novel and potential renewable energy source that can reduce dependency on fossil fuels. Moreover, incorporating crop residues into the soil can mitigate greenhouse gas emissions by sequestering carbon, thus contributing to climate change mitigation (Kumar *et al.*, 2023). Therefore, the effective management and utilization of crop residues and byproducts are essential for promoting agricultural sustainability, environmental conservation, and economic efficiency. Henceforth, this article explores the diverse forms of crop residues produced by various crops, their characteristics, and their implications for agricultural practices. Understanding their origin, composition, and potential uses is essential for optimizing their value in terms of energy, economy, and sustainability along with minimizing negative environmental impacts.

1.2 Origin and composition

Crop residues and byproducts are formed throughout the agricultural production cycle, starting from crop cultivation to post-harvest handling and processing. Using a grain-residue conversion factor, Shinde *et al.* (2022) reported the global production of crop residues, five billion metric tons in 2020−2021, which is more than three times higher than the 1960−1961 production levels. Globally, cereals account for 74% of crop residue production, 10% contributed by sugar crops, 8% by legumes, 5% by tubers, and just 3% by oilseed crops (Lal, 2005). Willer *et al.* (2020) reported yearly production of crop residue in different countries *viz.*, Brazil (518 Mt), UK (13 Mt), Sweden (4 Mt), Finland (3 Mt), Germany (42 Mt), France (48 Mt),

Spain (6 Mt), Italy (12 Mt), and Indonesia (55 Mt). According to the NITI Aayog Report, the amount of crop residues generated in India is about 620 Mt per year. Uttar Pradesh is the leading state in residue generation (115.64 Mt), followed by Andhra Pradesh (57.44 Mt), Punjab (50.38 Mt), Gujrat (47.71 Mt), and Haryana (36.39 Mt) (Bhattacharjya, Das, and Amat, 2021). Different varieties of crops yield different amounts and sizes of residue. In India, cereals (rice, wheat, maize, pearl millet, barley, minor millets, and sorghum) account for the majority of crop residue, accounting for 368 Mt (54%), followed by sugarcane (111 Mt) (16%). When it comes to individual crops, rice generates the most gross residues (154 Mt), followed by wheat (131 Mt) (Meena *et al.*, 2022). Fiber crop residues account for 20% of the total crop residue generated in the country. Cotton accounts for 74% of total fiber crop residue among fiber crops (Meena *et al.*, 2022).

The composition of crop residue varies widely depending on the type of crop, cultivation practices, and processing methods. Common constituents include carbohydrates (45−50% cellulose, 25−35% hemicellulose, and 15−20% lignin), proteins, lipids, vitamins, minerals, and bioactive compounds (Ginni *et al.*, 2021). For instance, cellulose content in wheat straw accounts for 37.73% (glucan), 0.86% (mannan), and 1.42% (galactan). However, the percentage of hemicelluloses varies from 28.79% xylan to 2.46% arabinan with 17.85% lignin (Gabhane *et al.*, 2020). Similarly, in rice straw the overall percentage of cellulose, hemicellulose, and lignin accounts for 37.3%, 28.58%, and 14.7%, respectively (Awogbemi and Kallon, 2023). However, in corn cob, it is 39.59%, 27.33%, and 18.93% for cellulose, hemicellulose, and lignin, respectively (Kim *et al.*, 2020).

The chemical composition of crop residues and byproducts determines their potential applications in various industries, including animal feed, biofuel production, biorefining, and soil amendment (Meena *et al.*, 2022; Ramos *et al.*, 2023).

1.3 Diverse forms of crop residues

Crop residues encompass a broad range of materials left over from agricultural activities, including crop cultivation and harvesting. The types of crop residues can vary depending on the crop types, cultivation practices, and harvesting methods. Here are several common types of crop residues:

1.3.1 Stems and stalks

Stems and stalks are the primary structural components of crop plants, providing support and facilitating nutrient and water transport. After harvest, they often remain in the field as significant crop residues (Tokas *et al.*, 2021). The main structural components of crops, such as corn, wheat, rice, and sugarcane, often form a significant portion of crop residues after harvest. For instance, maize produces approximately 1.0 to 1.5 tons of stalks per ton of grain that are rich in cellulose and hemicellulose, making them suitable for bioenergy production and soil mulching (Mohlala, 2018; Chaturvedi *et al.*, 2022). Similarly, sugarcane bagasse is the fibrous material remaining after the juice is extracted from sugarcane stalks. Studies have shown that when sugarcane is harvested, it consists of 75% stalk and 25% leaves and tops (Sindhu *et al.*, 2016). Bagasse contains 50% cellulose and 25% each of hemicellulose and lignin. Chemically, it contains about 50% α-cellulose, 30% pentosans, and 2.4% ash (Rezende *et al.*, 2011). Its high fiber and low ash content make it a suitable choice for the paper and sustainable textile industries (Costa *et al.*, 2013).

1.3.2 Leaves

The foliage of crop plants, including leaves, leaf sheaths, and fronds, contribute to crop residues. Leaves contain nutrients, such as nitrogen (N) and potassium (K), and organic matter that can decompose and enrich the soil (Maqsood *et al.*, 2022). Several crops such as olive, maize, soya bean, cassava, groundnut, tomato, cotton, sorghum, tea, etc. produce large amounts of leaf residue (Sakina *et al.*, 2023). Tea leaves, after pruning, contribute to leaf litter in plantations. These residues decompose slowly due to the presence of polyphenols but eventually enhance soil organic matter and fertility (Luo *et al.*, 2023). Olive leaves are produced as residue and byproducts during tree pruning in olive tree farms. These leaves are a rich source of cellulose, hemicellulose, lignin, and phenolic compounds (Espeso *et al.*, 2021). The composition is leveraged for bio-oil, biofuel, and bioenergy production through bio- and thermochemical treatments of the leaves (Najafi, Castro, and Karimi, 2021). However, olive leaf residues are also of special interest for their therapeutic effects and are generally used for producing phenol-rich olive leaf extracts (OLE) to be used in pharmaceutical and food applications (Apostolakis, Grigorakis, and Makris, 2014).

Traditional uses of leaf residue include animal feed, soil amendment, and energy generation (Awogbemi and Kallon, 2023). However, owing to their high nitrogen content, these are used as biofertilizers, composting, and bio-manure. Recently, a group of researchers (Qadri *et al.*, 2013) used sorghum leaves to produce nanorods in silicon carbide semiconductors, demonstrating the diverse applications of leaf crop residue. Hence, by leveraging novel technologies and

effective management strategies, these leaf residues can be transformed into bioenergy, converted into organic fertilizers or sustainable packaging materials, and even processed into animal feed supplements.

1.3.3 Husks and hulls

Protective coverings surrounding grains and seeds, such as corn husks, rice hulls, and oat hulls, are common crop residues (Joseph, 2024). Husks and hulls are often rich in cellulose and hemicellulose and can be used as animal bedding, mulch, or feedstock for bioenergy production (Goel, Thapliyal, and Arya, 2024). For instance, rice husks are high in silica, making them resistant to decomposition (Liang *et al.*, 2015). They are often used as a soil amendment, in biochar production, or as a substrate for growing mushrooms (M. Kordi *et al.*, 2024). Further, sunflower hulls, removed during seed processing, are used as animal bedding, mulch, or for bioenergy and biofuel production (Havrysh *et al.*, 2023). Similarly, peanut hulls are used in animal feed, as mulch, and for producing biochar. Owing to a slow decomposition rate, they are used in biochar production to enhance soil organic matter in the soil (Singh Yadav *et al.*, 2023).

1.3.4 Straw

The dried stalks and leaves, after the grain and chaff have been removed from cereal crops such as wheat, barley, and oats, are referred to as straw. Worldwide, wheat straw is the most significant byproduct of wheat processing, produced in large quantities (Hemdane *et al.*, 2016). Approximately 529 million tons of wheat straw are generated annually across the globe (Govumoni *et al.*, 2013). Wheat straw contains high levels of carbohydrates (lignin, cellulose, and hemicelluloses), proteins, minerals (Ca, P), silica, acid detergent fibers, and ash (Peng and Wu, 2010). It is also rich in bioactive compounds and vitamins (Tufail *et al.*, 2018). The concentration of macro- and micronutrients varies depending on the wheat variety and cultivar, plant growth stage, soil type, fertilizers used, and climatic conditions (Tufail *et al.*, 2018). Cereal straw has diverse applications, including its use as animal feed and in the production of bioethanol, biogas, nutraceuticals, and biofertilizers (Singh *et al.*, 2024; Kaldis *et al.*, 2020). Wheat and paddy straw are also used for biochar production to enhance soil quality and water retention capacity (Abbas *et al.*, 2020). Numerous studies have explored its use in eco-friendly construction, particularly in the form of straw bales (Tlaiji *et al.*, 2022) and as a component in particleboard and other composite materials. Recent research has identified paddy and wheat straw as a potential alternative for manufacturing bioplastics (Rai and Choure, 2023). Additionally, it serves as a substrate for mushroom cultivation, supporting the growth of mushroom spores (Ujagar and Rathod, 2021).

1.3.5 Stover

The term "stover" typically refers to the residual plant material left in the field after grain harvest. Corn stover, for example, includes the leaves, stalks, cobs, and husks remaining after corn kernels are harvested (Tyndall, Berg, and Colletti, 2011). They are the most important crop residue used as fodder, particularly in regions where grazing options are limited (an estimated 48.1 million tons per annum), followed by sorghum stover (6.5 million tons per annum) and wheat straw (2.7 million tons per annum) (Alemayehu, 2009). Stover finds extensive applications in animal bedding, feeding livestock, generating biogas, composting (Maeda and Ravindran, 2020), producing biochar (Ma *et al.*, 2024), and ethanol production (Elsagan *et al.*, 2023). In a study, it was reported that an ethanol yield of 91.94 g per kg of sorghum stover, without detoxification and washing of the pretreated biomass, following mild acid pretreatment, enzymatic hydrolysis, and fermentation (Akanksha *et al.*, 2016). Overall, stover is an essential component in sustainable farming practices, promoting soil health, livestock nutrition, and energy sustainability.

1.3.6 Root systems

Root residues include the underground parts of the plant left after harvesting the above-ground portions. These residues are crucial for soil structure and health, as they contribute to soil organic matter and microbial activity (Pržulj *et al.*, 2022). Root residues, from potatoes, carrots, and cassava, offer valuable opportunities for various applications (Moodley and Trois, 2024). These residues are commonly used in agricultural practices, including soil amendment and erosion control. Additionally, they serve as a source of organic matter, contributing to the overall health of the soil ecosystem. Root crop residues can also be used for animal feed, providing a nutritious supplement for livestock (Ncobela *et al.*, 2017). Moreover, these residues hold potential for bioenergy production through anaerobic digestion or as feedstock for biofuel production. Potato and cassava root residues have a high potential for ethanol production (Branca, Galgano, and Di Blasi, 2023) and the starch and flour industries (Sánchez *et al.*, 2017). The residues of the cassava industry can also be used to produce bio-oils after pyrolysis or be treated before saccharification, optimizing the process (Pattiya, 2011). With their diverse

applications and environmental benefits, root crop residues play a significant role in sustainable agriculture and resource management.

1.3.7 Pruning and trimmings

In perennial crops, such as fruit orchards and vineyards, pruning and trimmings from branches and vines contribute to crop residues. Pruning residues, when removed from the cultivated field, can be directed to energy conversion to obtain renewable forms of energy (heat and power) (Libutti, Cammerino, and Monteleone, 2021). In the European Union, fruit tree cultivation spans an area of 11.33 million hectares, potentially yielding around 25 million tons per year of pruning material (dry matter), assuming no other alternative uses are considered (Aliaño-González *et al.*, 2022). This biomass represents approximately 8.9 million tons of oil equivalent (Mtoe) per year in gross energy content, which could potentially generate up to 23.9 terawatt-hours (TWh) per year of power. In an experiment led by Gómez-Muñoz *et al.* (2016), the use of olive tree pruning as biochar was found to significantly enhance the retention of nitrogen in the soil, thereby illustrating the potential of this byproduct in contributing to sustainable soil management practices. Table 1.3 shows various crop residues and byproducts of different crops with their potential applications in multiple industries.

TABLE 1.3 Applications of crop residue and byproducts in multiple industries.

Crop residue/ Byproduct	Applications	Reference
Sugarcane Bagasse	Bio-compost, pulp and paper production enzyme production, bioethanol, organic acids, alkaloids, protein enriched cattle feed, antibiotics, biosurfactants, biosorbent	(Ahmad *et al.*, 2021; Kuila, Sharma, and Kuila, 2018; Maeda *et al.*, 2013)
Sugarcane Molasses	Sweetener, organic acid production, animal feed, fertilizer production, ethanol production, enzyme production, biosurfactant, baby food production, drugs, and medicine formulation	(He *et al.*, 2014; Arshad *et al.*, 2017; Jamir *et al.*, 2021)
Wheat bran	Biopolymers, substrate for enzyme production, biofuel production, bio-sorbent for toxins, cattle feed	(Javed *et al.*, 2012; Singh *et al.*, 2009; Palmarola-Adrados *et al.*, 2005)
Wheat straw	Animal feed, bedding for domestic animals, biofuel, ethanol production, biochar, bio-bricks, mushroom production, energy generation,	(Sarkar *et al.*, 2012; Tufail *et al.*, 2021)
Rice straw	Compost, biogas, source of cellulose and polyphenols in food and pharmaceutical industry, biomethane, bioethanol and biohydrogen production, reinforcer in packaging industry, bioplastic production, edible fruit coating agent	(Bilo *et al.*, 2018; Xue *et al.*, 2017; Ramos *et al.*, 2023)
Corn Stover	Bioethanol production, biomaterial in packaging industry, nanocellulose manufacturing, biochar, hydrochar, capacitor, enzyme production, bio-oil, biogas	(Zabed *et al.*, 2023; Duan *et al.*, 2024; Ngubane and Oyekola, 2023)
Barley straw husk and hull	Biochar, bioethanol, bio-sorbent, bio-composites, mushroom cultivation, oil spill sorbent, energy and power generation, animal feed, biochar, paper and pulp industry	(Mittal, Garg, and Bajpai, 2019; Pafcuga *et al.*, 2021; Hein, 2021)
Spent grain	Brewing byproducts, bioactive compounds, biopolymers	(Hejna, 2022)
Press cake (left after oil extraction)	Animal feed, bio-fertilizer, biofuel formation	(Rakita *et al.*, 2023; Latini *et al.*, 2023; Nježić *et al.*, 2023)
Peel, pulp, and pomace	Animal feed, compost formation, bio-fertilizers, ethanol production, bioactive compounds production, biofuel generation	(Jalal *et al.*, 2023; Rifna, Misra and Dwivedi, 2023; Mahish *et al.*, 2024)

1.4 Byproducts of processing

Byproducts of agricultural crops refer to secondary materials generated during the cultivation, harvesting, post-harvest processing, and utilization of crops. These byproducts have a high nutrient profile and often have value in various industries and applications, contributing to resource efficiency, economic sustainability, and environmental management. Examples include bran, meal, pomace, and hulls produced during milling, oil extraction, and fruit processing operations. These byproducts have various applications in animal feed, food processing, and bioenergy production. Some common byproducts of crops have been explained in this section:

1.4.1 Bran

Bran is the outer layer of cereal grains, such as wheat, rice, barley, and oats, separated during milling or processing (Papageorgiou and Skendi, 2018). It is rich in fiber, vitamins, minerals, and phytochemicals and is often used as livestock feed or a dietary fiber supplement for humans (Cheng *et al.*, 2022). Cereal bran is usually composed of three layers: pericarp, testa, and aleurone. These layers are rich in cellulose (10−23%), followed by hemicellulose (26−32%) and approximately 2.2 to 12.5% lignin (Arzami, Ho, and Mikkonen, 2022). These layers also have phenolic compounds, peptides, lipids, and pectin in small amounts (Ndolo and Beta, 2014). For instance, bran, a significant byproduct of wheat flour milling, makes up about 13 to 19% of total wheat grain weight depending on the milling process (wet or dry) used for its extraction (Hossain *et al.*, 2013). It finds diverse applications, with approximately 90% used as livestock feed and the remaining 10% incorporated into the food industry as a source of fiber in bakery items, fried foods, oil extraction, and breakfast cereals (Kim *et al.*, 2013; Abdel-Aal and Rabalski, 2013). The testa, aleurone, and pericarp of wheat consist of 33.463.0% dietary fiber, including xylans, lignin, cellulose, galactan, and fructans (Curti *et al.*, 2013). Additionally, wheat bran contains various vitamins, minerals, and bioactive compounds such as alkylresorcinols, ferulic acid, flavonoids, carotenoids, lignans, and sterols (Kim *et al.*, 2006). The bioactive compounds in cereal bran have been demonstrated to exhibit a variety of biological functions, including anti-inflammatory, anticancer, antibacterial, and cardiometabolic protective effects (Călinoiu and Vodnar, 2018). In addition, oat bran was reportedly linked to a reduced risk of chronic illnesses, such as hypertension, chronic gut inflammation (Xue *et al.*, 2021), and cancer (Xue *et al.*, 2022). The food and pharmaceutical sectors have been working to maximize the value of these byproducts. Nonetheless, a lot of work needs to be done to assure sustainability in the fortification process into more nutrient-dense and bioactive matrices, as well as in the pretreatment methods to increase the solubility and accessibility of the most intriguing components.

1.4.2 Husks

Husks are the outer coverings or protective layers of cereal grains, oilseeds, and legumes, such as rice husks, oat husks, coconut husks, and soybean husks (Grafi and Singiri, 2022). Untreated rice husk contains 75% organic matter, with 25% being ash residue. Its chemical makeup consists of 94.50% silica, 18% ash, and 3 to 4% oxides of iron, calcium, and magnesium, along with 34.8% nitrogen and additional nutrients (Varela Milla *et al.*, 2013). Rice husks are extensively utilized across various domains, including the creation of highly porous carbon fibers (Meekum and Wangkheeree, 2021), catalyst development, chip manufacturing, and the production of lightweight construction materials (Akeke *et al.*, 2013), biochar (Asadi *et al.*, 2021), and bio-sorbents (Syuhadah and Rohasliney, 2012). Studies indicate that integrating husks into the soil can notably enhance soil characteristics (Singh Karam *et al.*, 2022). This includes reducing soil bulk density, improving soil pH, augmenting organic carbon content, increasing nutrient availability, and eliminating heavy metals, thereby leading to enhanced crop yields (Nurhidayati and Mariati, 2014; Pratiwi and Shinogi, 2016).

1.4.3 Pomace

Pomaces are the fruit residues left after the pressing of grapes, extraction of fruit oils such as olives, or the distillation of fruits like cherries and apricots, primarily comprising fruit skins, pulp, stalks, and seeds (Follonier *et al.*, 2014). Traditionally considered low-value waste, pomaces are typically disposed of through landfilling, incineration, or composting (Chowdhary *et al.*, 2021). However, due to their composition (30% polysaccharides, 20% pectin, 15% proanthocyanins, lignin, and structural proteins), pomaces have been repurposed as sources of valuable products such as organic fertilizers and phenolic compounds (Iqbal, Schulz, and Rizvi, 2021). They also serve as substrates for fermentation and polyhydroxy alkanoates (PHAs) production (Corrado, Varriale, and Pezzella, 2023). Grape pomace contains substantial amounts of health-promoting nutrients. It is especially abundant in dietary fibers, which can make up to 85% of its composition depending on the grape variety, and polyphenolic compounds, about 70% of which remain in the pomace after the

winemaking process (Beres *et al.*, 2017). Exhausted olive pomace is the primary crop byproduct produced by olive pomace extraction industries. It contains valuable phenolic compounds and mannitol (Gómez-Cruz *et al.*, 2021). It has a high calorific value and is now used as a low-cost renewable fuel. Additionally, the resulting ashes can be employed in the production of ceramic materials (De La Casa and Castro, 2014).

1.4.4 Press cake

Press cake is the solid residue remaining after extracting oil or juice from oilseeds, nuts, or fruits using mechanical pressing (Ancuț;a and Sonia, 2020). It contains residual protein, fiber, and oil and is often used as animal feed or fertilizer (Jingura and Kamusoko, 2018). Soybean, rapeseed, and sunflower seeds are the most widely produced oilseeds globally, with respective production volumes of 337.9, 69.2, and 56.7 million tons (Rodríguez-Roque *et al.*, 2021). These are followed by linseed, camelina, coconut, cotton, pumpkin, and hempseed. Beyond oil extraction, the oil industry has also begun supplying protein-rich byproducts for animal feeds, taking advantage of the significant quantities of byproducts generated during the extraction process (Vidal *et al.*, 2022). These byproducts, known as oilseed press cakes, remain after most of the oil has been extracted. Press cakes obtained through mechanical pressing methods come in two forms: cold-pressed cakes, produced without heat, and expeller-pressed cakes, created by conditioning the oilseed with steam before pressing (Rakita *et al.*, 2023). These cakes are rich in fiber, residual oils (typically containing more than 10%), and essential fatty acids (Çakaloğlu, Özyurt, and Ötleş, 2018). The large availability and low cost make press cakes attractive raw materials, especially for obtaining and valorizing proteins and residual oils for various applications. Recently, Ribeiro *et al.* (2023) explored the potential of faveleira oilseed cake for cookie production. The byproduct from oil extraction of faveleira seeds represents a cost-effective raw material suitable for the creation of functional foods. They conducted an analysis of the physicochemical properties, chemical composition, and antioxidant activity of faveleira press cake flour for its application in cookie production and other baked goods. Due to its high antioxidant activity, significant polyphenol content, and richness in minerals and fiber, faveleira flour shows substantial potential for use in cookies and possibly in other bakery products such as bread, cakes, and pastas. Similarly, the coriander press cake is the byproduct obtained during the mechanical pressing of coriander seeds during oil extraction. Owing to its high protein (27%) and lignocellulose content (36%), along with thermoplastic and adhesive properties, it can be used to produce self-bonded particleboards through hot pressing (Evon *et al.*, 2023). It has also been found to significantly improve indoor air quality due to the presence of a terpene, linalool (Evon *et al.*, 2023).

1.4.5 Bagasse

Bagasse is the fibrous residue remaining after extracting juice from sugarcane or sorghum or processing other fibrous crops, such as bamboo or hemp (Alves, 2011). It is rich in cellulose and can be utilized as a biofuel feedstock, pulp and paper, or as a renewable material for composting or mulching (Wani *et al.*, 2023). A group of researchers (Vieira *et al.*, 2021) examined fermenting dilute acid-treated sugarcane bagasse-derived cellulose hydrolysate (with 13 g/L lactic acid) to produce an isopropanol−butanol−ethanol mixture using *Clostridium beijerinckii* DSM 6423. They achieved a yield of 10.03 g/L with a mixture of hydrolysate and sugarcane molasses. In another study, researchers (Prajapati *et al.*, 2020) explored the impact of enzymatic hydrolysis on ethanol production from sugarcane bagasse using *Candida shehatae* NCIM 3501. Their results revealed an ethanol yield of 0.415 g/g, with a maximum concentration reaching 15.54 g/L. Additionally, it is used as a bio-sorbent (Wang *et al.*, 2022), charcoal briquettes (Messay *et al.*, 2021), energy production and ceramic materials (Teixeira *et al.*, 2015), cement additive (Andreão *et al.*, 2019), in concrete (Payá *et al.*, 2002), as reinforcement in polymer composites (Khoo, Chow, and Ismail, 2018), and in various bioenergy production processes such as biogas (Nosratpour, Karimi, and Sadeghi, 2018), bioethanol, bio-hydrogen (Manish and Banerjee, 2008), and bio-jet fuel (Diederichs *et al.*, 2016). Moreover, it serves as a feedstock for several industrial processes including pyrolysis, gasification, steam reforming, combustion, and biochemical and chemical processes to produce a wide range of valuable products (Shabbirahmed *et al.*, 2022).

1.4.6 Pulp

Pulp is the fibrous residue obtained from processing fruits, vegetables, or other plant materials for juice extraction or fiber production (Maurya *et al.*, 2015). It can be used as animal feed, composting material, or bioenergy feedstock (Gottumukkala *et al.*, 2016). For instance, the residual sugar beet pulp comprises around 19% cellulose, 28% hemicelluloses, 18% pectin, and 8% protein, representing one of the most abundant vegetable wastes generated in Europe. The enzymatic breakdown of sugar beet pulp represents a crucial pathway for its conversion into valuable reducing sugars (Usmani *et al.*, 2022). These

sugars can then be subjected to additional processes to yield various beneficial products, including but not limited to bioethanol, bioplastics, and biogas, as well as chemicals such as prebiotics, furfural, and therapeutic compounds (Nirmal *et al.*, 2023; Rana *et al.*, 2022).

1.4.7 Spent grain

Spent grain is the residual grain left after brewing beer or distilling spirits, primarily barley or other cereal grains. It is often used as animal feed, particularly for livestock, or as a substrate for mushroom cultivation (Bolwig *et al.*, 2019). In the process of brewing beer, brewers' spent grain emerges as the primary byproduct, accounting for approximately 85% of the total byproducts generated (Rachwał *et al.*, 2020). It comprises the residual insoluble portion of barley grain after the mashing process and the separation of sweet liquid wort, a step known as lautering. Its dry matter encompasses cellulose, hemicellulose, lignin, proteins, lipids, and an ash fraction, along with soluble compounds like glucose, maltose, and malto-oligomers (Mussatto, 2014). The chemical composition of brewer's spent grain is influenced by various factors such as barley variety, harvest time, malting, and mashing conditions, as well as the type and quality of additives used in the brewing process (Zeko-Pivač *et al.*, 2022). Predominantly, it is composed of protein (15−26%) and fiber (35−60%) on a dry weight basis, with major proteins including hordeins, glutelins, albumins, and globulins. Hordeins, classified as B (30−50 kDa), C (55−80 kDa), and D hordeins (95 kDa), are particularly abundant (Ikram *et al.*, 2017). Due to its rich protein, fiber, and nutrient content, BSG finds extensive use in animal nutrition, primarily for pigs, fish, and poultry, and to a lesser extent in human nutrition (Bonifácio-Lopes, Teixeira, and Pintado, 2020). It serves as an energy source and has been reported to contribute to the production of bio-oil, biochar, and permanent gases through pyrolysis (Mussatto, 2014). Additionally, conventional applications of BSG include its use in pulp and paper production and as an adsorbent for removing dyes from wastewater or organic compounds from waste gases (Bonifácio-Lopes, Teixeira, and Pintado, 2020).

Overall, agricultural byproducts play a significant role in resource utilization, waste reduction, and value addition in agricultural and food systems. Efficient management and utilization of these byproducts are essential for promoting sustainability and circularity in agriculture.

1.5 Utilization and benefits

Crop residues and byproducts are valuable resources with diverse applications across agricultural, industrial, and environmental sectors (Figure 1.1). In livestock agriculture, crop residues serve as feed ingredients for livestock, providing

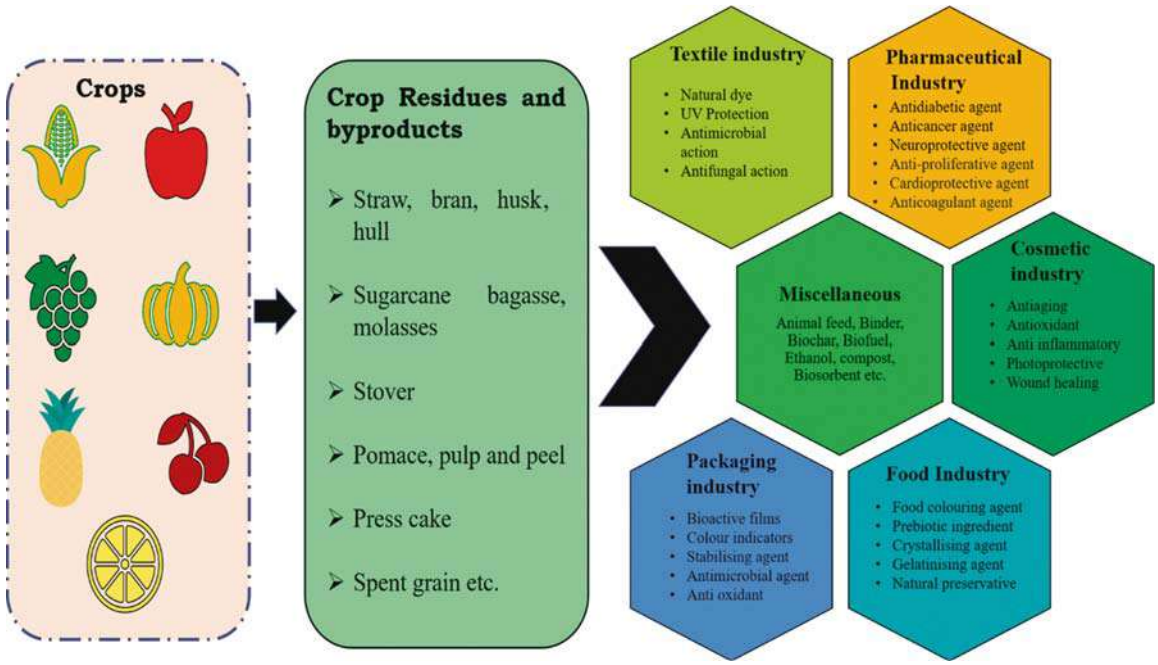


FIGURE 1.1 Various crop residue and byproducts with their applications. Crop residue and byproducts with their applications in various industries

essential nutrients and dietary fiber (Krishna and Mkondiwa, 2023). Byproducts such as bran, husks, and meal are used as feed supplements and additives, enhancing the nutritional value of animal diets (Shinde *et al.*, 2022). In addition to animal feed, crop residues and byproducts are used in bioenergy production, contributing to renewable energy sources and reducing dependence on fossil fuels (Havrysh *et al.*, 2023). Biofuel technologies, such as ethanol fermentation and biodiesel production, use agricultural biomass as feedstock, offering sustainable alternatives to conventional fuels (Koul, Yakoob, and Shah, 2022).

Furthermore, crop residues and byproducts are crucial in maintaining soil fertility and ecosystem health. Returning crop residues to the soil through conservation tillage, mulching, or composting improves soil structure, moisture retention, and nutrient cycling (M. Kordi *et al.*, 2024). The organic matter content of crop residues enhances soil microbial activity, promoting nutrient mineralization and carbon sequestration (Singh Yadav *et al.*, 2023). Farmers can improve soil health, reduce erosion, and mitigate greenhouse gas emissions by incorporating crop residues into agricultural systems, contributing to climate change adaptation and mitigation efforts (Nurhidayati and Mariati, 2014). While researchers have explored conventional products derived from valorizing crop residues and byproducts, ongoing developments are focusing on nonconventional and novel products that offer substantial benefits to humankind and the environment. Crop residues such as corn stover, wheat straw, and rice husks are being used to produce biodegradable plastics (Li *et al.*, 2023). Since these plastics are made from renewable resources and decompose naturally, they help in reducing reliance on fossil fuels and mitigating plastic pollution. The process involves converting the cellulose and hemicellulose in crop residues into biopolymers that can be used to manufacture packaging materials, utensils, and other plastic products. Furthermore, advanced technologies have enabled the production of bio-based chemicals and materials from crop residues (Cai *et al.*, 2024). Lignocellulosic biomass, derived from plant cell walls, can be converted into valuable chemicals such as ethanol, butanol, and acetic acid through fermentation processes (Beluhan *et al.*, 2023). These chemicals serve as precursors for a wide range of products, including solvents, adhesives, and coatings. Additionally, crop residues are being used to produce bio-composites, which are strong, lightweight materials used in automotive, aerospace, and construction industries (Gowda *et al.*, 2023). Additionally, crop residues like banana stems, pineapple leaves, and hemp stalks are being explored as sources of natural fibers for the textile industry (Akatwijuka *et al.*, 2024). These fibers are eco-friendly alternatives to synthetic fibers and conventional natural fibers like cotton. They are processed to produce fabrics that are biodegradable, durable, and require less water and pesticide for cultivation (Shafqat *et al.*, 2023). Innovations in textile manufacturing are enabling the production of high-quality, sustainable fabrics from agricultural residues. Several crop residues and byproducts, such as coconut shells, rice husks, and peanut shells, have been investigated for their potential in producing activated carbon (Kali *et al.*, 2024). This process involves carbonizing the biomass at high temperatures, followed by activation with steam or chemicals to create a porous structure. The resulting activated carbon has a high surface area and excellent adsorption properties, making it effective for removing contaminants and suitable for various industrial applications (Bhat *et al.*, 2023). Various researchers have explored the role of agro-waste in developing bio-enzyme mocktails. These enzymes are employed in various industrial processes, including textile processing, paper production, and biofuel generation (Benny *et al.*, 2023). For instance, cellulase and hemicellulase enzymes derived from crop residues can break down complex carbohydrates into simple sugars, which can then be fermented to produce biofuels like ethanol. Furthermore, the bio-enzyme mocktails are significantly used as organic fertilizers to promote plant growth in the horticulture industry. Moreover, these bio-enzymes also act as biocleaners for the degradation of solid waste owing to their hydrolytic properties. In 2015, the Arun and Sivashanmugam (2015) garbage enzyme was extracted from molasses obtained from the sugarcane processing industry, as well as from vegetables and fruits like tomatoes, cauliflower, pineapple, orange, and mango dregs. This extract was rich in enzymes, including protease, amylase, and lipase. When applied to dairy waste-activated sludge, the extract reduced total solids by 37.2%, suspended solids by 38.6%, and pathogens by 99%.

The conventional and novel applications of crop residues and byproducts are transforming agricultural waste into valuable resources. These innovative applications not only offer economic benefits to farmers and industries but also contribute to environmental sustainability by reducing waste, lowering carbon footprints, and promoting the use of renewable resources. As research and development continue to advance, the potential for crop residues to play a significant role in a sustainable future becomes increasingly evident.

1.6 Challenges and opportunities

Despite their numerous benefits, the effective utilization of crop residues and byproducts faces several challenges, including logistical restraints, market competition, and technological limitations, as shown in Figure 1.2 (Blasi *et al.*, 2023). The primary challenge posed by heaps of these crop residues is that in many parts of the world, crop residues are

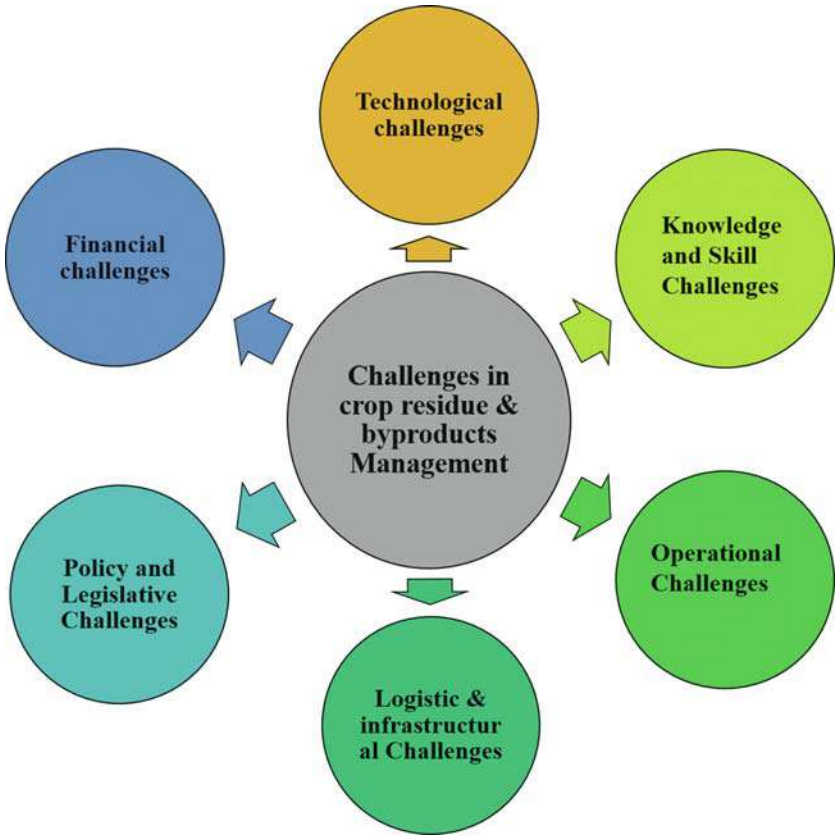


FIGURE 1.2 Various challenges in efficient management of crop residue and byproducts. Various challenges in efficient management of crop residue and byproducts

burned quickly to clear fields, leading to air pollution, greenhouse gas emissions, and health hazards (Tokas *et al.*, 2021). Management of crop residues requires gathering and transporting residues from fields to processing centers, which can be cost-prohibitive, particularly for farmers from third-world countries. Further, the efficient collection, storage, and transportation of crop residues require infrastructure, investments, and coordination among stakeholders, which is mostly lacking. Market fluctuations and price volatility influence the economic viability of crop residue utilization, affecting farmer incentives and industry profitability. Technological barriers, such as biomass conversion efficiency and product quality, hinder the development of advanced bioenergy and biorefining processes (Mohammad *et al.*, 2024). Moreover, developing markets for residue-based products, such as biofuels, bioplastics, and animal feed, requires significant investment and infrastructure. Converting residues into valuable products requires advanced technologies that are not always available or affordable for all farmers.

However, these challenges also present opportunities for innovation and collaboration among researchers, policymakers, and industry stakeholders. Advances in biomass conversion technologies, such as enzymatic hydrolysis, thermochemical conversion, and biorefinery platforms, offer promising solutions for maximizing the value of crop residues and byproducts (Chandel *et al.*, 2024). Integrated agricultural systems, incorporating crop rotation, cover cropping, and agroforestry, enhance the sustainability of crop production and increase the availability of biomass feedstock. Policy support and investment incentives for bioenergy and bioproduct industries facilitate market development and infrastructure expansion, fostering a transition toward a more sustainable and circular agricultural economy.

1.7 Conclusion and recommendation

Crop residues and byproducts represent valuable resources with diverse applications and benefits across agricultural, industrial, and environmental sectors. Understanding the origin and diversity of these materials is essential for optimizing their utilization and minimizing waste in agricultural production systems. The need of the hour is to recognize these crop residues and byproducts as a valuable resource and make the best use of them sustainably. By leveraging innovative technologies and sustainable practices, the full potential of crop residues and byproducts can be harnessed to enhance

agricultural productivity, resource efficiency, and environmental sustainability. Collaborative efforts among stakeholders are crucial for overcoming challenges and realizing the opportunities offered by these abundant and renewable resources. Here are a few future recommendations for stakeholders to unlock the full potential of crop residues and byproducts, driving sustainable agricultural practices, enhancing economic opportunities, and contributing to environmental conservation:

- Promoting research and development to explore innovative uses of crop residues and byproducts.
- Enhancing farmer awareness and education by conducting training programs and workshops to educate farmers on the benefits and methods of utilizing crop residues.
- Supporting policy and regulatory frameworks that incentivize the sustainable use of crop residues, such as subsidies, tax breaks, and grants for residue-based projects.
- Encouraging industry collaboration to foster partnerships between agricultural producers, researchers, and industries to develop market-driven solutions for crop residue utilization.
- Investing in infrastructure and technology for the collection, storage, and transportation of crop residues to processing facilities.
- Promoting sustainable practices that integrate residue management into routine farming activities.
- Facilitating market development for products derived from crop residues, such as bioenergy, bio-based materials, and animal feed.
- Supporting small-scale and local initiatives by providing financial and technical support to small-scale farmers and local communities to develop residue utilization projects.
- Fostering public-private partnerships between government agencies, private companies, and nonprofit organizations to leverage resources and expertise.

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Chapter 2

Livestock waste: Sources, types, and composition

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Chapter Outline

2.1. Introduction 21
2.2. Livestock production 22
2.3. Production of livestock wastes 22
2.4. Livestock wastes and environment 27
2.5. Environmental impact reduction 28
2.6. Odors associated with livestock wastes 29
2.7. Pathogens in livestock wastes 30
2.8. Livestock waste utilization 31
2.9. Conclusion 33
References 33

2.1 Introduction

Agricultural waste forms are one of the major global environmental issues affecting air, water, soil, and biodiversity, the world over. Agricultural wastes could be defined as the residual remains from the processing of various agricultural items in the form of solid or liquid, depending on the type of activity. Agricultural wastes include crop residues, food processing wastes, and agrochemical wastes, in addition to livestock wastes. Livestock wastes comprise manure and urine produced by many species of farm animals, along with leftover feed materials, bedding, and wash water from livestock holdings. In addition, a lot of waste is being produced in dairy processing plants, hatcheries, and slaughterhouses.

With the burgeoning human population and a drastic change in the lifestyle of people, there is a great demand for a supply of animal food products. As a result, there is an upsurge in the population of livestock and poultry to keep pace with the increased demand for products of animal origin. Of late, there has been a shift in the livestock production systems from extensive mixed farming systems to specialized farming systems with zero grazing under highly intensive conditions, otherwise referred to as confined animal feeding operations (CAFOs) (Sorathiya *et al.*, 2014). This has resulted in increased production of livestock wastes, causing deleterious effects on human, animal, and environmental health. An earlier study stated that highly intensive livestock and poultry production systems/CAFOs in the United States generated 369 million tons of manure.

Effective handling of livestock waste is a real challenge as far as the cost, safety of humans and the environment, and biosecurity are concerned. The negative impacts emanating from livestock wastes on the face of the Earth are numerous: environmental pollution, heavy metal contamination, biodiversity impacts, climate change impacts, challenges to food chain, and human and animal health impacts (Rodriguez-Eugenio, McLaughlin, and Pennock, 2018). There are reports to

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testify that the majority of the environmental ammonia pollution and high levels of antibiotics in air samples are generated from livestock farming (May, Romberger, and Poole, 2012).

It is important to manage livestock wastes effectively without any deleterious effect on the environment and food security of humans and animals. For this, the application of sustainable, eco-friendly, and economically viable management techniques should be sought. Innovative technologies are available to transform the livestock waste into wealth, benefiting not only the environment and human health but also improving the income of farmers. It is necessary to implement policies, develop infrastructure, and declare incentives to encourage the usage of such methodologies for sustainable management of livestock wastes, resulting in the waste-to-wealth concept.

Livestock wastes could be used to produce various types of organic manure (farmyard manure, biofertilizer, compost, vermicompost), generate energy, and manufacture biofuel and animal feed, thus harnessing the hidden potential to bring in sustainable farming and improved health status of soil, humans, crops, and animals. One of the remarkable outcomes of converting livestock waste to organic manure is the increased potential for engaging in organic agriculture. There is a need to develop and use appropriate technology to mitigate the negative effects. The mitigation strategies should suit different livestock production systems under varying agro-ecological and socioeconomic conditions and land use patterns.

A detailed insight into the source, type, and composition is needed for a comprehensive understanding of the sustainable methods of utilization of livestock wastes. It is imperative to conceptualize long-term solutions for effective management and utilization of wastes. The public health concerns due to the release of obnoxious odors and harmful pathogens resulting from ineffective methods of use of wastes should be addressed, so that the resilience of livestock production systems could be strengthened. The possibility of reduction, reuse, and recycling should also be focused on. Only then can the path for a way forward roadmap be made. This should aim at effective utilization of the resources from wastes, resulting in a clean environment and sustainable livestock farming. The chapter outlines an in-depth review of the source, types, composition, and effective utilization of livestock wastes in a healthy, economic, and sustainable manner.

2.2 Livestock production

According to Koop and van Leeuwen (2017), the global human population is supposed to reach 9.7 billion by 2050 and 11.2 billion by 2100. This demands a significant rise in the production of agricultural crops and livestock products, thus creating the scope of generating a large quantity of wastes from both these sectors. Two basic types of livestock production include intensive and extensive systems. In an intensive system, many animals are reared indoors, resulting in a large quantity of waste being produced at a particular locality. Here, the quantity of livestock wastes produced far exceeds the limit that can be utilized locally as manure (Vanotti *et al.*, 2009). In the case of extensive systems, animals are generally reared outdoors, where the wastes produced get spread out on a large area and do not get accumulated at a particular location. The population of livestock (in millions) in India as per the 20th Livestock Census (2019) is presented in Table 2.1.

2.3 Production of livestock wastes

2.3.1 Wastes from different livestock species

Increased production of livestock wastes occurs from different species of domestic animals, generally referred to as farm animals. These wastes include animal excreta, urine, leftover feed, waste fodder, bedding materials, and wash water from animal holdings. There should be appropriate technology to render these wastes safe and useful. Otherwise, the wastes pose a great threat to biosecurity, the environment, and the health of humans and animals. It is pertinent to have a basic understanding of the different species of livestock and the waste production potential of each to design appropriate ways of handling and managing livestock wastes. It has been reported that from a herd of 25 to 30 cows, biowastes of 10 to 30 kg/day and wastewater of 2 m^3/day could be obtained for biogas production (Sinsuw, Wuisang, and Chu, 2021). Sources of livestock waste are presented in Figure 2.1.

2.3.1.1 Dung/animal excreta

2.3.1.1.1 Cattle and buffaloes The quantity of dung produced by cattle and buffaloes varies with the age of the animal, breed and size, season, feed provided, and the type of farming system.

TABLE 2.1 **Population of livestock (in millions) in India as per 20th Livestock Census, 2019.**

Species	Population (millions)	Rank in the world
Cattle	193.46	2
Buffalo	109.85	1
Sheep	74.26	3
Goat	148.88	2
Pig	9.06	10
Poultry	851.81	5

(**Source:** 20th Livestock Census, 2019.)

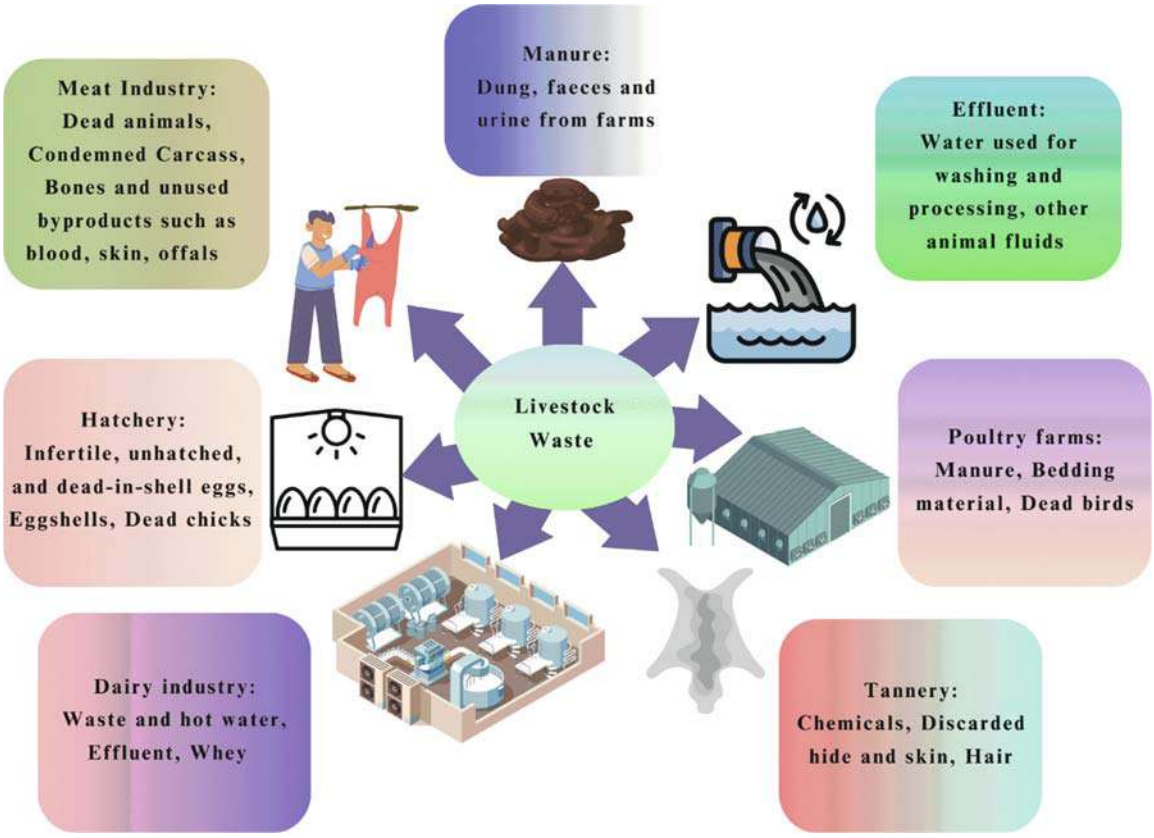


FIGURE 2.1 **Sources of livestock wastes.**

2.3.1.1.2 Sheep and goats Sheep and goats are generally reared in India and many of the tropical countries by grazing in open areas and common property resources (CPR) rather than under indoor rearing situations. Also, sheep and goats are generally penned in agricultural fields during the night, the dung pellets voided thereof being incorporated into the land itself. As a result, the recovery of dung from these species will be very limited. On average, the estimated dung production from sheep and goats in India is to the tune of 40.85 million tons and 20.18 million tons, respectively, per year (Sastry and Thomas, 2021).

2.3.1.1.3 Pigs and poultry Pigs are being reared under scavenging systems in rural locations of many tropical countries. Of late, intensification of pig production is gaining significance. Poultry is being reared for different purposes as for egg

production (layer) and for meat (broiler). There are breeders as well. Even though backyard rearing of poultry is persistent over rural areas, intensification and commercialization of poultry production have come into existence. This results in accumulation of excreta (poultry litter) at different locations where farming takes place.

2.3.2 Wastes from different livestock processing systems

Slaughterhouse wastes, wastes from milk processing plants, and wastes from hatcheries and tanneries are the major wastes produced from livestock processing systems. In addition, these operations generate wastewater, having a high content of organic matter and therefore a high biological oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). Slaughter of farm animals is carried out in around 892 registered units in India, apart from many animals and birds being slaughtered in small roadside facilities in rural areas (Basic Animal Husbandry Statistics, 2020).

2.3.2.1 Wastes from slaughter of cattle, buffalo, sheep, goats, and pigs

The wastes from slaughterhouses include hide/skin, heads of animals, meat trimmings, condemned meat, feet, hooves, horns (from horned animals), inedible offal from thoracic and abdominal regions (lungs, stomach, intestines), contents from stomach and intestines, bones, blood fetal remains, tails, and hair (Sastry and Thomas, 2021). Skin will not be a major waste from pig slaughter, as it is considered edible.

2.3.2.2 Wastes from slaughter of poultry

Wastes produced in poultry slaughter differ from that produced in slaughterhouses processing buffaloes, sheep, goats, and pigs. Feathers are a different item in addition to heads, intestines, and inedible offal, legs, fat, and skin (sometimes, when the skin is discarded).

2.3.2.3 Wastes from dairy processing plants

In cooperative dairy units, a major share of the milk procured is processed as pasteurized milk. Milk is used for the preparation of different value-added products as well. Dairy processing units generate liquid wastes with a BOD of 1.89 kg m^3, the quantity of which varies from 2 and 6 m^3/m^3 milk processed. Most of the water used for various processes in dairy units is ultimately converted as effluents, with a COD load of about 8 kg/m^3 of milk processed. For example, one of the important byproducts generated in dairy processing plants is whey (liquid remaining after subjecting curdled milk to straining).

2.3.2.4 Wastes from poultry hatcheries

Lots of hatchery operations take place in different locations in the poultry sector to produce quality chicks. The major wastes generated include infertile, unhatched, and dead-in-shell eggs, eggshells, and dead chicks.

2.3.3 Economic considerations in using livestock wastes

Livestock wastes encompass economic as well as environmental benefits. Livestock waste management holds a significant role in the livelihoods of people in many countries (Arthur and Baidoo, 2011; Parihar *et al.*, 2019). Incorporation of farmyard manure into soil will help in maintaining the fertility of the soil and provide other economic benefits such as improvement of the physical condition of the soil, retention of nutrients, and improving the water holding capacity. Spreading of dry manure into agricultural fields could be considered as a cost-effective strategy to replace chemical fertilizers (Dadrasnia *et al.*, 2021). Chojnacka, Moustakas, and Witek-Krowiak (2020) postulated that the financial value of manure depends on the market value of the plant nutrients that could be replaced by the manure. Some of the important economic benefits include generation of bioenergy, which can be a substitute for fossil fuels, and biogas, which can provide a renewable and environmentally friendly fuel source for households. The switch over from conventional and nonrenewable sources of energy to renewable biogas is an economic benefit to rural households worldwide, as is taking place in China; this change in power generation has resulted in creating substantial revenue (Huang *et al.*, 2022; Zhang and Xu, 2020). Anaerobic digestion of crop residues as a cost-effective method may reduce the harmful effects of burning and/or leaving the residues in the field, causing major air and soil pollution. Likewise, anaerobic digestion of livestock wastes has been recommended as a cost-effective method to meet the escalating demand for energy. In addition, use of biogas has social benefits, too, as there is gainful employment generation and gaining of extra income through bioelectricity production (Sinsuw, Wuisang, and Chu, 2021).

Economic benefits also result from the efficiency of utilization of wastes into value-added products. On the other hand, substantial environmental benefits arise from the processing of wastes, which bring in mitigation of deleterious effects in the health of humans and animals. It is difficult to attribute a specific economic value to environmental benefits due to factors that hinder the exact evaluation of the benefits accrued to the environment (Sampat *et al.*, 2021). Innes (2000) also reiterated that environmental benefits of utilization of livestock wastes could not be monitored directly. Presently, processing of wastes and conversion to value-added products is fraught with a lot of barriers, with the high cost of investment involved. The competition from the use of technologies for the generation of energy and other value-added products from nonrenewable sources is also to be considered a barrier in the effective use of technologies for utilization of wastes from livestock. The effectiveness of technologies for processing livestock wastes was found to be limited by numerous economic barriers, including lack of adequate space for utilization in crop agriculture and for lack of suitable incentives for the promotion of the use of such practices. Sampat, Ruiz-Mercado, and Zavala (2018) analyzed the cost-effectiveness of different technologies used to produce value-added products from organic matter in dairy wastes in a Wisconsin city. It was found that sustainable waste management could be considered as a viable opportunity only when incentives were provided. Astill and Shumway (2016) examined the economic feasibility of processing dairy wastes to mitigate air and water pollution under two technological innovations.

2.3.4 Characteristics of livestock wastes

The characteristics of livestock wastes depend on various factors such as the livestock rearing systems, species and age of the animal, density of animals in the system, type and quantity of feed provided, composition and digestibility of feed, quantity of waste bedding material, and wastewater produced in the system (Martín-Marroquín and Hidalgo, 2015). It was postulated that wastes having 20 to 25% solids content could be considered solid wastes, the characteristics of which will depend on the type of solids present. According to Malomo, Madugu, and Bolu (2018), livestock wastes could be classified based on their consistency as solid manure (>25% solids), semi-solid manure (5−25% solids), and liquid manure (<5% solids). On the other hand, waste with 4 to 10% solids content is considered as liquid waste and is usually handled with flushing/irrigation consistency (Martín-Marroquín and Hidalgo, 2015).

2.3.4.1 Physical parameters

Wastes generated at animal holdings could be of solid, liquid, or slurry type, depending on the solid content of the product. One of the important solid components of livestock wastes includes dung, which comprises the undigested residue of feed and fodder materials excreted by the animals. According to Erickson and Kalscheur (2019), the nutrients that are not utilized by the animal are excreted from the body as dung/droppings. Poultry farms, in general, produce a dry mixture of wastes inclusive of droppings, litter material, waste feed, and sometimes soil from the ground (Zhang and Westerman, 1997). It has been estimated that poultry litter consists of 92.5% total solids, out of which 40.3% has been found to be volatile solids. Around 43.9% of the total solids are constituted by ash (Priyadarsan *et al.*, 2001).

On the other hand, dairy and pig farms usually produce a diluted form of waste containing dung, urine, unused feed and fodder, and wash water. The dung produced by livestock depends on the species of the animal and the type of feed consumed by the animal (Lysyk, Easton and Evenson, 1985). Dung production potential varies with different species of farm animals, with cattle producing around 18 to 30 kg of dung per day; buffaloes, 25 to 40 kg; and pigs, 3 to 5 kg (Arthur and Baidoo, 2011).

2.3.4.2 Chemical composition

The chemical composition of livestock wastes depends on many factors. Sebek *et al.* (2014) reported that the quantity of nutrients available in the manure varied with the location, age, species, feed intake, and utility of the animal. According to the National Research Council (2001), the major nutrients excreted by animals are of feed origin. The nutrients of importance in animal manure, based on soil application, are nitrogen, phosphorus, and potassium (Malomo, Madugu, and Bolu, 2018). Livestock waste has been found to be rich in nitrogen and phosphorus (Abdeshahian *et al.*, 2016; Ho *et al.*, 2013), and after composting, the composition changed with improved fertility. Shahid *et al.* (2016) reiterated that in addition to nitrogen and phosphorus, livestock waste is a good source of plant nutrients such as calcium, magnesium, and sulfur.

According to Arthur and Baidoo (2011), dung from cattle contains 77% moisture, 20% organic matter, 0.32% nitrogen, 0.14% phosphorus, 0.30% potassium, and 0.40% calcium. It has been reported that around 55 to 90% of the nitrogen and phosphorus content of the feed will be excreted through dung and urine (FAO, 2019). Phosphorus is present in grains and oilseeds as phytate (50−70%). A major proportion of the phytate is excreted by simple-stomached farm animals (pigs) as

these animals do not possess phytase enzyme (Ravindran, Bryden, and Kornegay, 1995). In the case of sows with piglets, the dietary excretion of nitrogen will be 75 to 80% of dietary intake, and for growing pigs, the value will be 70 to 80% of dietary intake. The corresponding proportion, based on dietary intake, for the excretion of phosphorus in the case of sows with litters and growing pigs includes 75 to 85% each. On the other hand, livestock wastewater is found to contain a high concentration of nitrogen (Varel, 1997). It has been found that wastewater contained in covered storage tanks lost nearly 20 to 30% of the nitrogen during the storage and handling process. The loss is of high proportion (55−80%) when wastewater has been stored in anaerobic lagoons. The nitrogen, phosphorus, and potassium content of dung from different species is presented in Table 2.2.

2.3.4.3 Factors affecting quality of livestock wastes

Many factors are found to affect the quality of livestock wastes. There exists a high variability in the composition of wastes obtained from livestock depending on the locality. The significant factors affecting the quality of livestock wastes could be generally classified as environmental factors, animal factors, patterns of livestock feeding and storage, and methods of handling waste (Celi *et al.*, 2017). On an earlier occasion, Ogbuewu *et al.* (2012) also reported that body size of the animal, diet composition, feed conversion rate, and utility of the animal species have a significant effect on the composition of livestock wastes. The type of livestock production system also has been found to affect the composition of wastes from livestock. The major factors affecting the quality of livestock wastes are discussed in this section.

2.3.4.3.1 Environmental factors Among the weather parameters, seasonal changes in the rainfall and ambient temperature are the major factors affecting the quality of livestock wastes. Annual variations in weather conditions, for example, changes in ambient temperature, could affect the quality of livestock waste. This is mainly because high temperature increases enzymatic activity, leading to the production of ammonia, which causes the loss of nitrogen from manure.

2.3.4.3.2 Animal factors There are many animal factors that cause variation in the composition of livestock wastes, especially manure. These include the species of the animal, stage of growth, utility of the animal, and the physiological state of the animal (such as gestation), and lactation. It is a fact that some nutrients are retained by animals for physiological functions (such as milk production and growth), and the rest are excreted (Erickson and Kalscheur, 2019; Sebek *et al.*, 2014). It has also been stated that factors such as the quantity of milk production and ration composition affect the quality of manure from livestock.

2.3.4.3.3 Pattern of feeding livestock Different strategies adopted for feeding different classes of animals based on physiological status cause changes in the quality of manure. According to FAO (2019), different quantity and quality of nutrients are fed to animals in gestation and lactation. It is common practice that certain minerals are provided to livestock by means of supplementation with mineral mixture, thereby resulting in excess supply. The quality of manure depends on the fiber content of the ration, especially roughages, and the digestibility of the ingredients. The amount of water consumed by the animal has also been found to affect the composition of manure; this is based on the species, age, feed intake, and temperature in the barn (FAO, 2019). There are many management measures used for mitigation of heat stress in farm animals, especially during summer season. One such method is the use of water for washing/cooling the animal and the animal holding; this could be another factor influencing the amount of water content in manure.

TABLE 2.2 Nitrogen, phosphorus, and potassium content of dung from different species.

Livestock waste	N %	P %	K %	References
Cow dung	1.86	0.82	2.11	(Adekiya *et al.*, 2020)
Poultry manure	2.91	0.84	3.79	
Pig dung	2.16	0.80	2.16	
Buffalo dung	1.23	0.55	0.69	(FAO, 2019)
Duck manure	2.15	1.13	1.15	

2.3.4.4 Storage and handling of waste

The physical and chemical characteristics of livestock wastes have a significant bearing on their potential use as an organic fertilizer. The method of handling and treatment causes changes in the quality (Malomo, Madugu, and Bolu, 2018). The system of collection of manure from animal holdings also influences the composition of manure. For example, when collection involves some amount of soil also, the content of ash will be more, and carbon content is reduced. The loss of nitrogen due to volatilization depends on the design and structure of storage tank, the amount of surface area that is exposed to air, and the amount of rainfall entering the storage facility (Dadrasnia *et al.*, 2021). Integration of manure into soil at the earliest could help prevent this. In addition, subjecting livestock wastes to different types of treatment protocols (physical, chemical, biological, and bio-thermal) results in improving the quality of manure.

2.4 Livestock wastes and environment

With the increase in the population of farm livestock, there is the generation of a large quantity of wastes. Livestock waste is mostly organic in nature (degradable waste), which includes animal and fodder/feed residues, dung/droppings, and wash water forming sludge; these can cause serious negative impacts on the environment and can be a potential threat to human and animal health (Li *et al.*, 2020; Misslin *et al.*, 2022). The unsustainable approaches of livestock production and waste management have resulted in environment pollution, habitat degradation, incidence of infections in humans and animals, and climate change effects. Livestock wastes, if not handled and managed efficiently, will lead to numerous negative impacts on the environment by means of emitting obnoxious odors, heavy metal poisoning, pesticide residues, and coliform contamination. These negative effects further end up affecting the health of humans and animals collectively. According to Gerber *et al.* (2005), on the other hand, livestock wastes have the potential to be an economically profitable and environmentally sound asset, provided efficient treatment and management techniques are employed. When properly used, livestock wastes have the quality to improve the soil organic matter resulting in enriching the soil, and when inappropriately managed, the same can pose severe threats to water, soil, and air, endangering the environment as well as human and animal health.

Effective management and disposal of livestock wastes has now become a challenge on account of biosecurity and environmental safety. Therefore, it is inevitable that efficient protocols be employed by which these wastes could be managed in an environmentally sound, safe, and sustainable manner to mitigate the negative impacts. This becomes more important as livestock wastes form the major source of obnoxious gases and odors and the origin of pathogens. Waste management techniques such as composting, vermicomposting, and use of manure for bioenergy generation can be considered to mitigate the adverse impacts on human, animal, and environmental health. The effects of livestock waste on the quality of water, air, soil, and human and animal health and its potential in generating greenhouse gases are reviewed in this section. The methods of mitigating the negative effects on the environment are also delineated.

2.4.1 Effect on water quality

The methods by which water gets polluted by livestock wastes have been found to be very complex. In general, when nutrients from livestock wastes become more in soil, they accumulate and saturate soil. At this point, the nutrients are lost to surface or groundwater by leaching and runoff. The phosphorus: nitrogen ratio in manure is almost twice the requirement by crops, and excess phosphorus is released, causing pollution of surface water when excess manure is applied to soil. This is also associated with algal overgrowth (algal blooms) and fish-kills, thus seriously affecting biodiversity. Nitrogen and phosphorus are important soil nutrients in livestock wastes that have the potential to pollute water. Free ammonia has more impact on water due to high toxicity to many species of fish. In addition to nitrogen, potassium and heavy metals such as cadmium and lead in manure can contribute to water pollution (NRC, 2001).

Liquid effluents in livestock wastes contain harmful pathogens. Direct discharge of manure to waterways and its percolation to groundwater are to be considered dangerous (FAO, 2019). It has been reported that excess amounts of dissolved carbon in livestock wastes resulted in reducing the oxygen content in water, thus increasing the biological oxygen demand (BOD). The net effect was the formation of oxygen-depleted dead zones in both inland and marine surface water (Halden and Schwab, 2008). Many reports state that drinking water gets easily contaminated by effluents from livestock wastes, whereby a substantial load of pathogenic microorganisms enters the surface water column.

2.4.2 Effect on soil quality

Incorporation of manure is an important means of replenishing the organic matter in soil, especially in organic agriculture, wherein the use of chemical fertilizers is prohibited. The use of organic fertilizers has been considered a better alternative to

chemical fertilizers for improving soil fertility and achieving higher crop yields, thus bringing in sustainability in agriculture production. Contamination of soil is a persistent problem resulting from excessive incorporation of livestock wastes in agricultural fields. It has been found that heavy metals such as cadmium and lead and other elements (nitrogen, phosphorus, and potassium) present in manure can cause soil pollution (NRC, 2001).

2.4.3 Effect on air quality

Air quality becomes poor due to the release of toxic gases and odoriferous substances, particulates, and bio-aerosols containing an array of pathogens. According to the National Research Council (2001), elements such as nitrogen, phosphorus, and potassium and heavy metals (cadmium and lead) are found to cause air pollution due to excess runoff when applied to crops. Airborne emissions of such toxic gases and particulate matter (endotoxins, ammonia, hydrogen sulfide, nitrous oxide, methane, many volatile organic compounds) arise from livestock farms and from stored dung and urine of animals because of microbial digestion. Exposure to these substances will lead to a wide range of respiratory infections in humans (May, Romberger, and Poole, 2012).

2.4.4 Effect on human and animal health

The major issue as far as human and animal health is concerned is the contamination of surface and ground water sources, soil, and air with chemicals, microorganisms, and parasites. The spread of zoonotic diseases is of great concern. In the case of a disease outbreak among farm animals, livestock wastes often form the major vector for transmission of zoonotic infections, in the absence of effective biosecurity measures. Roubik *et al.* (2017) reported that livestock wastes contain residues of antibiotics, hormones, and heavy metals along with certain pathogenic microorganisms; these can cause harmful effects on human and animal health. Some of the harmful pathogens in livestock wastes have been discussed in Section 6. Inappropriate handling of livestock wastes also could result in the introduction of larval/infective stages of many parasites (foodborne trematodes, cysticercosis) in the food chain, causing infections in humans and animals. Cliver (2009) suggested that zoonotic diseases get transmitted to humans while consuming raw leafy vegetables contaminated with organisms present in manure or from contaminated water used for irrigation.

An important group of chemicals of serious concern that could be present in livestock wastes is endocrine-disrupting compounds (EDC). These compounds may be organic or inorganic in nature and can occur in manure as natural constituents or come in through drugs administered through the feed of livestock used as food animals. These constituents can interfere with hormonal signaling in both humans and animals and can mimic the function of estrogenic or androgenic hormones, thereby causing adverse health effects (Union, 2014). Examples of such EDCs include steroids (Combalbert *et al.*, 2012), and such ECDs have an effect on health because of the interaction between soil, water, and air.

2.4.5 Emission of greenhouse gases

Stored livestock wastes result in decomposition of organic matter and can cause substantial emissions of greenhouse gases (GHG) into the atmosphere (Co_2, CH_4, and N_2O). The emissions from livestock wastes could be directly associated with several environmental problems such as eutrophication, acidification, and climate change (Sohil and Kichloo, 2023). Large-scale production of livestock wastes along with surface application of manure in agricultural fields exacerbates this situation, resulting in global warming (Ogbuewu *et al.*, 2012).

Emission of methane occurs because of enteric fermentation of feed ingredients or from organic manure from different species stored under anaerobic conditions by the action of obligate methanogenic microorganisms. Methane emission per animal per day will generally depend on the feed intake of ruminants, the degree of inclusion of fat, the forage: concentrate ratio of the diet, the digestibility of feed, and the inclusion of feed additives. On the other hand, the level of nitrous oxide emission is linked to emission from soil in which manure has been incorporated (Junior *et al.*, 2013). It is to be noted that methane and nitrous oxide are the two major GHGs associated with global warming effects. As far as ammonia is concerned, the major source is hydrolysis of urea in the urine of animals by the enzyme urease and is dependent on factors such as pH, temperature, and wind velocity.

2.5 Environmental impact reduction

- The wastes generated by livestock activity can be used effectively for gaining wealth and at the same time can lead to disaster causing negative impacts on the environment, if not handled and managed appropriately. The mitigation measures by which the negative effects caused by improper handling of wastes from livestock can be reduced have been discussed in this section. The following are some of the major considerations for mitigating the negative impacts of

livestock wastes on the environment (Hill, Owens, and Tchounwou, 2005; Hooda *et al.*, 2000; McGechan and Wu, 1998; Sampat *et al.*, 2021).

- Organic manure should not be applied more than the requirement of the crop and soil. This may lead to leaching and pollution of the environment.
- Diluting manure with water can be practiced for better penetration into soil. This can also help reduce surface runoff.
- Nutritional interventions in the system of rearing ruminants by which the amount of nitrogen and phosphorus can be reduced in fecal output. This will also help to reduce GHG emissions.
- Reduce stocking density of ruminants while grazing. This would help to reduce loss of organic matter due to runoff.
- Recovering phosphorus from organic manure, as uptake of phosphorus is less in soil.
- Storage of manure in the farm helps to kill the pathogenic microbes that can cause impairment of human and animal health.

2.6 Odors associated with livestock wastes

Odors associated with livestock wastes form one of the common sources of air pollution and have gained much attention because of adverse impacts on human and environmental health. Odor is a combination of different entities such as sulfurous compounds, indolic compounds and phenolic compounds, and volatile fatty acids and ammonia along with volatile amines. The development of specific odors and their source and emission characteristics have been reviewed by Wang, Huang, and Jiang (2023). The production of odors depends on the species of livestock, type of feed, weather conditions, type of animal housing, and manure handling systems. Odorants vary with respect to molecular structure and their physicochemical characteristics such as vapor pressure and solubility (Bierling *et al.*, 2021). The different strategies to reduce odors from livestock farms could be classified as physical, chemical, and biological techniques.

2.6.1 Sources of odors

In general, odors are emitted from landfills, sewage treatment plants, and food processing industries (Fisher, Alvarez-Gaitan, and Stuetz, 2019), whereas emission of odors also occurs in livestock farms, especially large-scale intensive farms. Wang *et al.* (2021) reported that maximum concentration of odors arises from compost areas and barns. Odors are generated in livestock and poultry farms during decomposition of dung/droppings, during storage, and during incorporation into soil, whereas the main source of gaseous odor emission in pig farms is storage of manure (Chen *et al.*, 2020).

2.6.2 Implications of odors from livestock wastes

It has been reported that odors from livestock wastes could seriously affect human, animal, and environmental health (Cao, Zheng, and Dong, 2023). Exposure to different odors via the olfactory pathway can result in inflammatory problems, affect emotions, and cause stress and depression symptoms in humans (Bratman *et al.*, 2024). Long-term exposure to different unpleasant odors emitted from livestock wastes containing hydrogen sulfide and volatile organic compounds could make human beings suffer from headache, eye irritation, and respiratory problems and lead to negative emotional problems (Conti, Guarino, and Bacenetti, 2020). Short-term exposure to odors also results in negative impacts.

2.6.3 Additives to reduce odors

The use of additives has been found to reduce odors from livestock wastes. Manure additives are products comprising microbial flora that are added to stored manure for minimizing emission of odors. Maurer *et al.* (2017) reported that additives have shown considerable potential in reducing up to 68% of ammonia and about 90% of volatile organic compounds, on an experimental basis in pilot studies. On the other hand, Chen *et al.* (2020) stated that many of the manure additives, including those acted on by microbial action, did not significantly reduce gaseous odors from pig manure (containing gases such as ammonia, hydrogen sulfide, and volatile organic compounds). Application of sodium bisulfite on manure has been practiced in the United States for reduction of odors (Szogi, Vanotti, and Ro, 2015).

2.6.4 Nutritional management strategies to reduce odors

Nutritional interventions could be tried to reduce odors from livestock wastes. According to Sutton and Richert (2004), using high-quality protein sources in pig feed could bring about reduction in nitrogen excretion, thereby reducing ammonia odor. Reducing excretion of phosphorus through manure can be brought about by avoiding supplementation with dietary phosphorus and by the addition of phytase as a supplement in rations. Reduction of non-starch

polysaccharides and maintaining the correct acid-base buffer in the ration can cause significant reduction in odorous compounds.

2.7 Pathogens in livestock wastes

Livestock wastes contain numerous microorganisms such as bacteria, viruses, fungi, and protozoa causing health risks to humans and animals by means of the contamination of air, water, and the environment. Zoonoses caused by microbial pathogens originating from livestock wastes are of great concern. This concern becomes enhanced due to the incidence of waterborne disease outbreaks attributed to fecal contamination of manure origin. This could be due to elevated concentrations of pathogens in the wastes generated on livestock and poultry farms. According to Sobsey *et al.* (2006), factors influencing the survival of pathogens in livestock wastes include temperature, drying, presence of ammonia, enzymes, microbial predation, proteolytic activity, and pH. In addition, the system of housing many animals in less space also leads to the concentration of wastes within the premises, contributing to environmental contamination.

2.7.1 Prevalence of microbes

Livestock wastes come under biodegradable wastes as they could undergo decomposition with the help of aerobic and anaerobic microorganisms (Ayilara *et al.*, 2020; Bhat *et al.*, 2018). The organic manure formed from the dung/droppings of livestock and poultry also contains several non-pathogenic microbes that are beneficial for soil health. Fresh or degraded livestock wastes such as manure, used bedding materials, leftover feed, and wastewater from farms are commonly used as fertilizer. Biological soil amendments of animal origin (BSAAO) are frequently employed to improve the productivity of soil, thereby improving crop productivity. Wang, Huang, and Jiang (2023) opined that soil contamination from livestock wastes, particularly the microbial criteria for soil amendments, frequently surpassed the stipulated standards outlined in the Food Safety Modernization Act (FSMA). Apart from the potential health risks posed to both humans and animals by many animal pathogens, there is an increasing concern regarding the elevated levels of antibiotics and antibiotic-resistant bacteria found in agricultural animal manures (Witte, 1998). Findings of Zalewska *et al.* (2021) indicated a notable presence of various antibiotic resistance genes (ARGs) in livestock and poultry wastes.

2.7.2 Microbes of public health concern

Human pathogenic bacteria (HPB) present in livestock wastes can migrate to soils when applied as organic fertilizer. In a study, Li *et al.* (2020) established an HPB database comprising 565 bacterial strains from different levels of application of cattle, pig, and poultry manure into different soil microcosms. It was found that across all manure and soil samples, 30 HPB were identified; the application of poultry manure revealed the highest levels of HPB in soil samples.

2.7.2.1 Bacteria

Sobsey et al. (2006) identified several bacteria in livestock wastes: *Aeromonas hydrophila, Arcobacter butzleri, Bacillus anthracis, Brucella abortus, Campylobacter jejuni, Chlamydia psittaci, Clostridium perfringens, Clostridium botulinum, Coxiella burnetiid, E. coli, Erysipelothrix rhusiopathiae, Francisella tularensis, Leptospira interrogans* and other species, *Mycobacterium* spp., *Salmonella* spp., and *Yersinia* spp. Studies by Bicudo and Goyal (2003) and Chen and Jiang (2014) found that among the numerous microbes associated with pathogenic diseases linked to livestock wastes, the most prevalent bacteria included *Salmonella*, *Campylobacter, Yersinia, Listeria monocytogenes,* and *Escherichia coli*. The impact of microorganisms originating from livestock wastes on air quality cannot be overlooked. Animals housed in barns along with their excreta and leftover feed serve as significant sources of microbes. Commonly isolated microorganisms from the air in the sheds of cattle, pigs, and poultry include bacteria from the genera *Streptococcus, Staphylococcus, Bacillus, Clostridium,* and members of the family Enterobacteriaceae. Bioaerosol-borne bacteria not only pose risks of infection but also exert immune-toxic and allergic effects. Gram-positive bacteria have been found to primarily dominate bioaerosol particles (Chmielowiec-Korzeniowska *et al.*, 2021).

2.7.2.2 Parasites and protozoa

There exists a high risk of environmental contamination with zoonotic parasites and protozoa via livestock wastes. Use of organic manure for the cultivation of fruits and vegetables has heightened the potential of transmission of zoonotic parasites. Livestock waste commonly carries the eggs of helminth parasites such as *Ascaris suum* and *Fasciola* spp., which can be transferred to humans through improper handling of animal waste. Moreover, the direct contamination of surface

water with animal manure has also been an important contributor to causing diseases involving zoonotic parasites (Murrell and Nawa, 1998). *Balantidium coli, Toxoplasma gondii, Cryptosporidium parvum, Cyclospora, Isospora* and *Eimeria, Giardia lamblia,* and *Microsporidia* are some of the protozoa getting transmitted to humans through contamination from livestock wastes.

2.7.2.3 Viruses

Livestock wastes can harbor a diverse range of viruses. These include Enteroviruses, Rotaviruses, Adenoviruses, Hepatitis E viruses, Caliciviruses, Reoviruses, Parvoviruses, and other nonenveloped viruses. Viruses such as Caliciviruses, Rotaviruses, and Hepatitis E viruses have the potential to infect humans (Sobsey et al., 2006). Infections caused by human enteric and respiratory viruses transmitted through fecal-contaminated food and water have been extensively documented. Certain Reoviruses, particularly type 3, exhibit a broad host range, which includes humans. However, the transmission of fecal-associated viruses originating from animals to human hosts is relatively uncommon. This could be attributed to the inherent specificity of these viruses to their respective hosts. A study conducted by Kwok et al. (2020) revealed that Picornaviridae, Parvoviridae, and Astroviridae were among the most frequently identified virus families in common farm animals.

Swine HEV has been demonstrated to be experimentally transmissible to primates, while human HEV is infectious for swine. Additionally, viruses like Aphthovirus (foot and mouth disease) and swine vesicular disease virus (SVDV), both members of the Picornaviridae family, can be transmitted to humans via aerosols or ingestion of contaminated food products from infected cattle and pigs (Morgan-Capner, 1998). Bovine enterovirus (BEV) has been recognized as a specific marker for identifying cow fecal contamination in wastewater, as noted by Ley, Higgins, and Fayer (2002). On the other hand, Hepatitis E virus (HEV) has been used as an indicator of swine fecal contamination in treated wastewater and surface water, as demonstrated in studies by Masclaux *et al.* (2014) and Gentry-Shields *et al.* (2015).

2.8 Livestock waste utilization

Livestock wastes have been utilized as manure for crops and for the generation of bioenergy in many countries. Dried dung from cattle and buffaloes are used as dung cakes for cooking in India. The intensification of livestock farming demands more efficient and large-scale sustainable techniques for utilization of livestock wastes.

2.8.1 Biofuel

The reliance on petroleum products has driven us to explore the potential of livestock waste for generating various forms of energy, with biogas emerging as a leading option in many countries.

2.8.1.1 Biogas

Anaerobic digestion of biomass is a well-known method for generating gas that serves as an efficient and clean renewable energy source, offering a viable alternative to nonrenewable fuels. One ton of manure with 20% solid content can produce 20 to 25 cubic meters of biogas, translating to a total energy value of 100 to 125 kWh. This can be converted into approximately 35 to 40 kWh of electricity and 55 to 75 kWh of heat energy. India and China are the two leading countries that use biogas for household cooking. The bottling of biogas was attempted and was able to successfully produce pure biogas with 98% methane content, which was compressed to 150 bar pressure for filling in cylinders in India (Sorathiya *et al.*, 2014).

2.8.1.2 Biodiesel

Slaughterhouse and poultry wastes, being high in protein, serve as excellent substrates for biofuel production. Biofuels can be in solid, liquid, and gaseous forms. Solid biofuels include charcoal, wood, and pellets, while liquid forms comprise biodiesel and bioethanol. Gaseous biofuel is primarily in the form of biogas. Given the energetic and biological properties of poultry and slaughterhouse wastes, they can be sustainably converted into bioenergy via biochemical or thermochemical processes such as anaerobic digestion, pyrolysis, and trans-esterification of poultry tallow (Hollas *et al.*, 2024).

2.8.2 Organic fertilizer

The utilization of livestock waste as organic fertilizer is an environmentally sustainable practice that transforms agricultural byproducts into valuable resources. This method addresses waste management challenges while enhancing soil fertility and

crop productivity. Various techniques such as direct application, composting, and anaerobic digestion offer diverse benefits suited to different farming needs, thus promoting eco-friendly agriculture.

2.8.2.1 Composting

Composting is a rapid bio-oxidation process where organic matter undergoes a thermophilic phase (45−65°C), during which microorganisms such as bacteria and fungi release heat, carbon dioxide, and water. This process transforms diverse organic materials into a uniform, stable, humus-like product through turning or aeration. The resulting compost is odorless, finely textured, has low moisture content, and can be used as an organic fertilizer. Additionally, composting biological waste with poultry manure effectively conserves the nitrogen in the manure, enhancing its fertilizer value and reducing the potential for ammonia to cause environmental pollution. The advantages of composting include enriching soil with organic matter, improving soil structure, and minimizing risk of soil erosion. Through composting, the weight and moisture content of manure are reduced, and its stability is increased. Compost is more manageable than raw manure and can be stored efficiently without causing odors or attracting flies, thereby reducing pollution risks. A user-friendly and cost-effective model of compost-making has been developed at Kerala Agricultural University, India, using selected bacterial cultures that act on livestock wastes, resulting in the formation of compost within 45 to 90 days, thus ensuring effective recycling of organic biomass (Xavier, 2011). The method of composting livestock waste is presented in Figure 2.2.

2.8.2.2 Vermicomposting

Earthworms consume organic matter in livestock wastes and excrete it as small pellets called vermicompost. During this process, essential plant nutrients like nitrogen, phosphorus, potassium, and calcium in the organic wastes are released and transformed into more soluble forms that plants can readily use. Vermicompost also contains biologically active substances, such as plant growth regulators. Vermicomposting increases the content of N, P, and K by 3 to 4 times and reduces composting time to 60 to 75 days. There are various species of earthworms, such as *Eiseniafoetida* (red earthworm), *Eudrilus eugeniae* (night crawlers), and *Perionyx excavatus.* The red earthworm is particularly favored due to its high reproduction rate, converting organic matter into vermicompost within 45 to 50 days (Parihar *et al.*, 2019).

2.8.3 Animal feed

By converting the byproducts from slaughterhouses (offal, bones, blood, feathers, dead animals) into various protein, fat, and mineral products like meat and bone meal, feather meal, and blood meal, the sustainability of food animal production can be significantly improved. Most rendered protein products are utilized as animal feed. These products are particularly valuable to the livestock and pet food industries due to their high protein content, digestible amino acids (notably lysine), available minerals (notably, calcium and phosphorus), and cost-effectiveness relative to their nutritional value. Using such

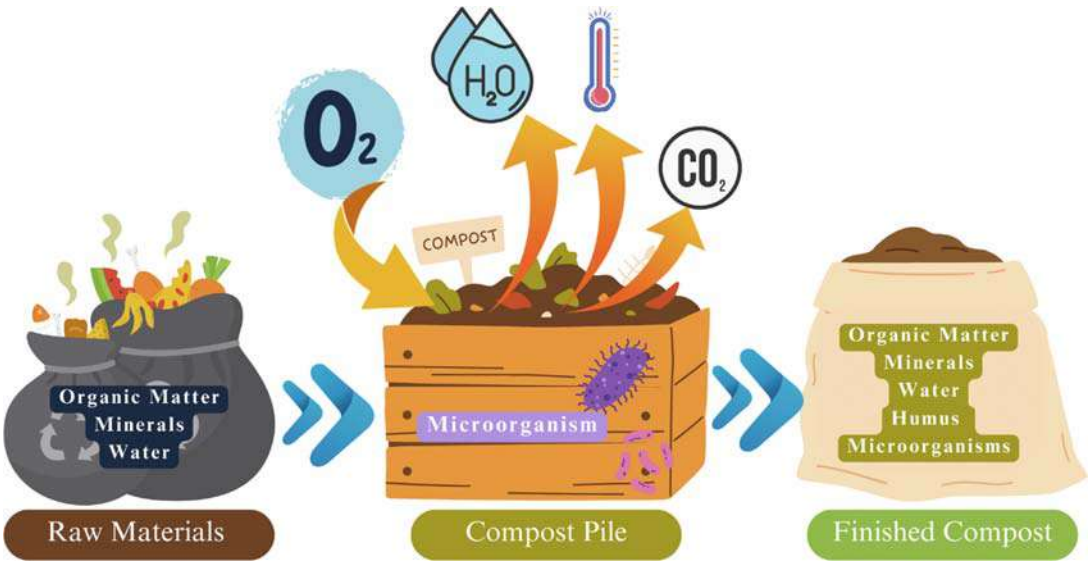


FIGURE 2.2 **Method of composting livestock wastes.**

reclaimed and recycled materials in pet food has been suggested to be a far more sustainable practice than using food intended for human consumption (Meeker and Meisinger, 2015).

Breeding black soldier fly (BSF) larvae offers a unique solution for managing livestock waste. Although adult BSFs have a lifespan of just a few days, their larvae can survive for several weeks, during which they consume large amounts of livestock wastes. This process yields two valuable byproducts: the residue or castings, which enhance soil fertility, and the larvae, which serve as a high-quality food source for various animals, including fish and birds (Hosseindoust *et al.*, 2024).

2.9 Conclusion

The rising demand for food of plant and animal origin has resulted in the generation of large quantity of wastes. To mitigate the harmful effects and to create wealth from wastes, there is a need for a strategic plan to promote research in sustainable utilization of wastes of livestock origin. For the formulation of appropriate technologies for effective handling and management, there should be proper understanding of the source, types, and composition of these wastes. This chapter outlined an in-depth analysis of these features with an emphasis on the deleterious effects on humans, animals, soil, and the environment and the mitigation measures. The methods by which livestock wastes could be effectively utilized in a healthy and sustainable manner have also been delineated along with economic considerations. The farmers, policy-makers, management specialists, and technologists should work in unison to evolve strategies for fully realizing the potential of livestock waste and its conversion into wealth.

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Chapter 3

Pesticide and chemical waste: Exploring the sources, composition, and characteristics

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Chapter Outline

3.1. Introduction 37
3.2. Occurrence, distribution, and possible sources of agricultural pesticide 38
3.3. Nano-pesticides and nano-fertilizers from natural (plant/animal) wastes 39
3.4. Occurrence, distribution, and possible sources of agricultural chemicals 40
3.5. Environmental impact and ecological consequences of pesticide and chemical waste 40
3.6. Technological advances in pesticide and waste management 43
3.7. Conclusion 44
References 45

3.1 Introduction

Pesticides are a class of chemicals used to kill bacteria, fungi, insects, weeds, and other organisms. They are typically referred to as herbicides, bactericides, fungicides, insecticides, or rodenticides. While most pesticides are effective against a broad range of pests and weeds, some are designed to target particular pests or diseases (Jayaraj, Megha, and Sreedev, 2016).

Studies have revealed that nearly one-third of the yield had increased after the use of pesticides. The use of pesticides worldwide increased by 81% from 1990 to 4.1 million tons annually in 2017. Between 2006 and 2015, 111,000 to 168,000 fatalities annually, or 14 to 20% of all suicides worldwide, were caused by pesticides. Approximately 14 million individuals have committed suicide themselves by consuming pesticides since the Green Revolution. Approximately 20,000 people die as a result of pesticide poisonings that happen annually (Boedeker *et al.*, 2020). There are now 2 million tons of pesticides used globally, of which 47.5% are herbicides, 30% are insecticides, 18% are fungicides, and 5.5% are other kinds (Rajput *et al.*, 2022).

In recent years, it was observed that China was the largest pesticide consumer globally with 1.76 million metric tons, followed by the United States (408 thousand tons), Brazil (377 thousand tons), and Argentina (204 thousand tons). One

Waste to Resources. https://doi.org/10.1016/B978-0-443-30246-6.00003-4
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study indicated increased pesticide usage in developing countries, including Cambodia, Laos, and Vietnam. In Asia, India is a significant pesticide producer of organochlorine, including benzene hexachloride and DDT (Pathak *et al.*, 2022).

These chemicals were accidentally released into aquatic environments by soil erosion, aerial sprinkling, drifting sprinkling, and the carelessness of dumping chemicals to clean tools. Due to heavy chemical exposure, consumption increased exponentially, leading to a potential threat to healthy beings by transferring these chemicals into the food chain through biomagnification and accumulation methods (Naidu *et al.*, 2021). Most of these substances are engineered to interfere with the target organism's physiological processes, resulting in malfunction and decreased vigor. Despite its advantages to agriculture sectors, it mainly impacts predator-prey interaction and damages biodiversity (Bashir *et al.*, 2020).

Some pesticides cause severe poisoning, including fatal blood cancer and multiple organ failure. The most common and highly toxic is paraquat, which also causes severe lung disorders that lead to respiratory failure and death (Rajmohan, Chandrasekaran, and Varjani, 2020). The present chapter mainly focuses on agricultural pesticides and chemicals distribution, possible sources, and how they impact the environment and biota.

3.2 Occurrence, distribution, and possible sources of agricultural pesticide

A wide range of chemicals and pesticides are being utilized more often worldwide. These chemicals have been created to restrict, reduce, prevent, or eradicate pests such as fungi (fungicides), insects (insecticides), rodents (rodenticides), weeds (weedicides), mollusks (molluscicides), and nematodes (nematicides) (Ahmad *et al.*, 2024). In the past, organochlorine pesticides were used widely in the agriculture sector; later, it was found that they could be converted into transformed products (TPs) and degradation products such as DDT, which is harmful to nature (Kalyabina *et al.*, 2021).

When modern formulations of new pesticides were introduced in recent years, they had to avoid PBT (persistent, bioaccumulative, and toxic) properties. The pesticides are divided into two classes: natural and synthetic. Natural pesticides, also called biopesticides, are produced by living beings such as fungi, plants, and bacteria. Biopesticides are divided into three major classes: biochemical pesticides, microbial pesticides, and plant-combined protectants (Kalyabina *et al.*, 2021). Another class of pesticides is synthetic, which is further categorized into four major categories (Figure 3.1). The first one is organochlorine pesticides, which are synthetic pesticides widely used in agriculture. They belong to a group of chlorinated hydrocarbon derivatives—for example, DDT, lindane, chlordane, and endosulfan. Another type is organo-phosphorus compounds, which contain a central phosphate molecule with alkyl or aromatic substituents—for example, malathion, parathion, chlorpyrifos, and diazinon (Hassaan and El Nemr, 2020). Carbamate pesticide compounds have a hydrogen atom, an alcohol group, and a methyl group in their basic framework—for example, methiocarb, aldicarb, carbaryl, and carbofuran. Pyrethroid pesticides are derived from pyrethrins, insecticidal chemicals in natural pyrethrum collected from chrysanthemum flowers (Ahamad and Kumar, 2023).

In contrast to crop accumulation, pesticides can travel long distances in the air, soil, and water, making them a significant cause of pollution in ecosystems. The significant ways that agrochemicals pollute the air are through aerial or

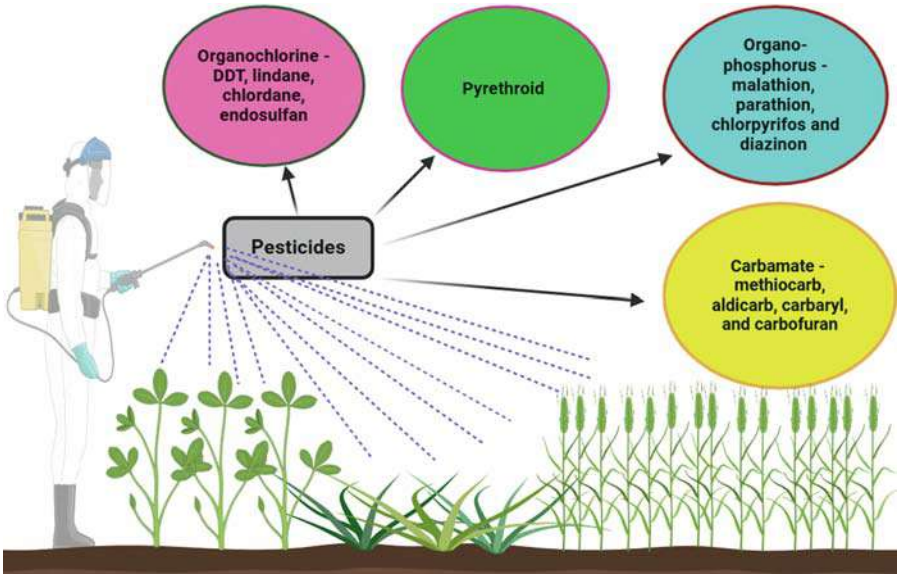


FIGURE 3.1 **Pesticides and their types with examples.**

ground spraying techniques. Pesticides are present in the air due to fumigation of crops to protect from pests. However, due to semi-volatile properties, pesticides are mainly deposited on airborne aerosol particles. Atmospheric precipitation can carry pesticides into water bodies, and these dissolved or attached particles to soil particles can accumulate in river sediment. The leading cause of soil contamination is the direct application of pesticides to the soil in order to protect the crops (Kalyabina *et al.*, 2021).

The most common source of pesticide entry into the environment is agricultural practices. These practices include runoff, field sprayers, and accidental spills, which come from the accumulation of these compounds in runoff water. This runoff water goes to aquatic bodies, which is highly fatal for aquatic well-being (Ore *et al.*, 2023). In recent times, to protect pesticides from rapid degradation, various modern formulations have been considered, such as adding nonionic surfactants such as alkylphenol ethoxylates (APEOs), alcohol ethoxylates (AEOs), and alkylamine ethoxylates (ANEOs), organosiliconepolyethoxylates, and polyethoxylated tallow amines (Kalyabina *et al.*, 2021).

3.3 Nano-pesticides and nano-fertilizers from natural (plant/animal) wastes

The field of agriculture might benefit immensely from the novel use of nanotechnology, which has transformed nearly every element of science. This sector could reveal novel aspects of contemporary agricultural methods if further explored. To transform these traditional waste-based fertilizers and insecticides into their nano-forms, researchers have invented nanotechnology to create nano-pesticides and nano-fertilizers. In the modern approach, these chemical fertilizers and synthetic pesticides reduce their size in nano-form through physical and chemical including mechanical milling, chemical etching, laser ablation, sputtering, and explosion processes and biological methods (using microorganisms) (Singh *et al.*, 2021a). However, turning bio-organic wastes into nano-agrochemicals would be safer and more economically feasible.

Nano-fertilizers and pesticides were made using a variety of techniques. However, green synthesis has lately attracted more interest, which was prepared by combining plant extract with a metal solution to create nanoparticles. To extract the active elements from plant and animal waste products and transform them into nanostructured compounds to create nano-agrochemicals. The macro- and micronutrients that promote plant development, as well as phenols, flavonoids, terpenes, sesquiterpenoids, and isoquinoline alkaloids with anti-pesticidal properties, make up the active ingredients (Batool, Nazir, and Majeed Zargar, 2024). The researcher developed a nano-metal citrate complex between mineral and plant waste citrate from pomegranate peel, which further precipitated into nano-form. The prepared nano-biofertilizer provides the plants with complete macro- and micronutrition (Batool, Nazir, and Majeed Zargar, 2024).

Nano-fertilizers are divided into two classes in terms of nutrient elements: macro- and micronutrient elements, or nano biofertilizers. They help to solve nutrient deficiencies, enhance crop quality and yield, and have less impact on the environment (Figure 3.2). Macronutrient elements include phosphorus, nitrogen, and potassium in the nanoscale, and micronutrient elements have small quantity nutrient requirements like zinc, which impacts disease resistance in crops. Another type of nano-fertilizer is chitosan nanoparticle-based nano-fertilizer. Chitosan, as a biopesticide, is a natural

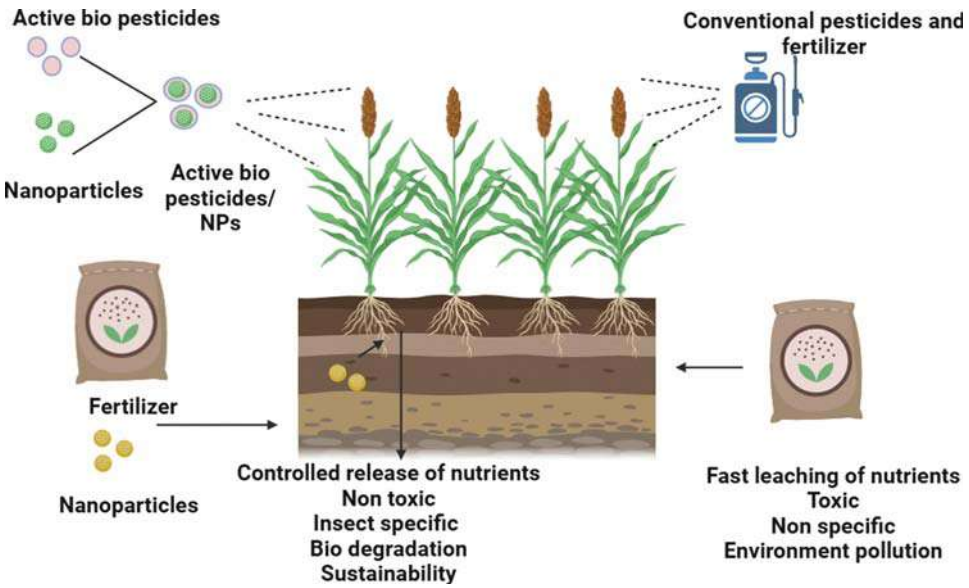


FIGURE 3.2 **Comparison of conventional pesticides and fertilizer versus nano-pesticides and nano-fertilizers.**

polymer of chitin. It has shown antibacterial, insecticidal, and antifungal properties, making it a sustainable alternative to fungicides (Jampílek and Kráľová, 2017)—chitosan nanoparticles in combination with NPK (nitrogen, phosphorus, potassium) nano-fertilizer. Nano-pesticides are found in different forms, such as nanoemulsion (lipid), polymer-based, nano-capsule-based, and metal-organic frameworks.

Nano-fertilizers and nano-pesticides have numerous advantages, such as high nutrient efficiency, selectivity, cost-effectiveness, rapid large-scale manufacturing, and environmental sustainability (Tang *et al.*, 2024). They have controlled releases, highly selective and highly efficient nutrients, and less adverse environmental impacts (Figure 3.2).

3.3.1 Limitations of nano-pesticides and nano-fertilizers: Future prospects

Nanoparticles are used to produce nano-fertilizers and nano-pesticides to solve the hurdles of traditional agrochemicals. However, preparing nano-pesticides and nano-fertilizers presents several challenges due to their adverse effects. Numerous studies carried out over time have demonstrated that mineral nanoparticles, when used as nano-agrochemicals, have several negative impacts on different physiological and morphological parameters, which eventually hamper plant growth. Consider the symbiotic connection between rhizobia and roots, germination percentage, root length, shoot length, and root hydraulic conductivity (Zulfiqar *et al.*, 2019).

Medicinal plants are used to counter this problem. Their extract acts as a potent reducing agent in the formation of nanoparticles. Regulation and safety concerns are another significant challenge (Tang *et al.*, 2024). Health risk assessments and solid regulatory frameworks are required for farmers, consumers, and the environment to be safe from their use in agriculture. In addition, proper understanding and further exploration of the methods or processes needed to make nano-fertilizers and nano-pesticides without any adverse impacts are also necessary.

3.4 Occurrence, distribution, and possible sources of agricultural chemicals

Agricultural chemicals include a wide range of substances used in farming and agriculture. They consist of a variety of substances, both natural and artificial, that are vital to crop yield, soil health, and pest management. These chemicals include macro- and micronutrients, fertilizers, pharmaceutical compounds, endocrine disruptors, and commonly found pesticides and herbicides (Tudi *et al.*, 2021).

Some endocrine disruptors bisphenol-A, triclosan, triclocarbon, 4-nonylphenol, 4-tert octylphenol, methyl paraben, propyl paraben, butyl paraben, benzyl butyl phthalate, di (2-ethylhexyl) phthalate, and di-n-butyl phthalate. These exogenous substances modify the actions of the endocrine system. In the past year, studies showed the prevalence and distribution of endocrine-disrupting substances in soil and water and any possible hazards to human health (Saha *et al.*, 2022). Similarly, pharmaceutical and personal care products, artificial sweeteners, and pesticides are frequently found in industrial and agriculture runoff water. The most common source of agricultural chemicals in water and soil was agricultural and industrial activities (Lee *et al.*, 2019).

Herbicides are pesticides that kill unwanted weeds or plants over the crops. The most widely used herbicides are glyphosate and atrazine. Some herbicides act as plant growth regulators. Polyethoxylated alkylamines and POEA (surfactants) are used as constituents of glyphosate-based herbicides, which are highly toxic. Low exposure to the herbicide glyphosate can significantly lower seed quality, leading to infertile agricultural areas (Rajmohan, Chandrasekaran, and Varjani, 2020).

Pesticides are another common type of chemicals in agriculture, such as DDT, lindane, chlordane, endosulfan, malathion, and parathion. Various studies have demonstrated the presence of pesticides in surface, groundwater, river water, ocean, soil, and biota. Their significant sources are agricultural runoff, reckless disposal, and industrial chemicals leaching into the water or soil. Overuse of pesticides leads to alarming situations in many developing countries. The low amount of exposure in humans and aquatic organisms causes serious repercussions. It eventually disturbs the whole food web, leading to disturbing ecological diversity (Pathak *et al.*, 2022) (Figure 3.3).

3.5 Environmental impact and ecological consequences of pesticide and chemical waste

3.5.1 Mechanisms of pesticide action of insecticides, herbicides, and fungicides in different organisms

Pesticides are biological agents known for their high persistence and pervasive nature. According to their nature, chemical structure, doses, and targets, these synthetic chemicals, along with the product of their bio-transformation, may remain in and interact with the environment and living organisms in many ways (Lushchak *et al.*, 2018). Pesticides are designed to be

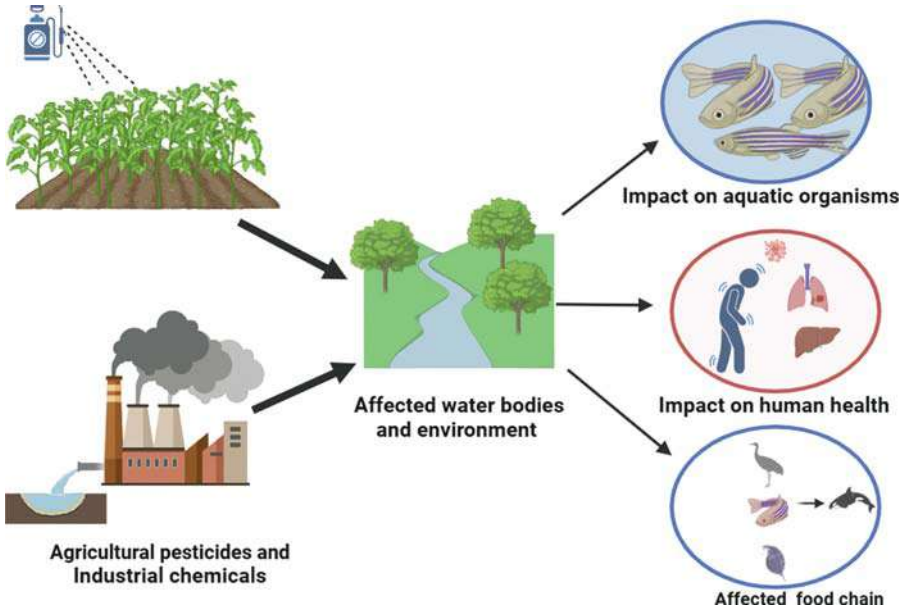


FIGURE 3.3 **Agro-pesticides and chemical source, transport, impact on environment or biota.**

more toxic to target pests than to non-target organisms, including humans. The mechanism or mode of action of various pesticides in different organisms is diverse and cannot specifically be classified.

While pesticide toxicity generally depends on temperature, dose, permeation rate, and degradation time, selectivity is based on differences in functional systems, such as the presence or absence of specific enzymes or receptors to attack the target molecules. Pesticides' primary action typically starts when the pesticide, along with its bioactive forms, binds to and interacts with the target molecules. This interaction further initiates a series of events that may be harmful or lethal to the pest so that it is no longer a viable competitor.

It is a well-known fact that insecticides act primarily on four nerve targets, including acetylcholinesterase (AChE), the voltage-gated chloride channels, the acetylcholine receptors, and the γ-aminobutyric acid receptor (GABA), systems that are generally located in animals but not in plants (Grünewald and Siefert, 2019). In contrast, herbicides mainly affect plant-specific pathways by inhibiting processes such as photosynthesis, carotenoid or plastoquinone synthesis, and the synthesis of essential compounds like aromatic and branched-chain amino acids, fatty acids, lipids, pyrimidines, or cell walls, which are crucial in plants but not in mammals. Moreover, many fungicides interfere with ergosterol (the fungal sterol), tubulin biosynthesis, or cytochrome c reductase, while others disrupt fundamental cellular functions (Casida, 2009).

However, minimal pesticide dose reaches the primary target. Mostly, it is diverted to secondary targets, where it is metabolically degraded. These secondary interactions usually occur at higher concentrations, while primary interactions occur at picomolar or nanomolar levels, although not always. There may be several targets with similar sensitivity but differing importance. For example, chlorpyrifos inhibits not only acetylcholinesterase (AChE1) but also several other serine lipases and amide hydrolases in trout brain, which, although equally or more sensitive, are not necessarily significant secondary targets (Greer *et al.*, 2019). Similarly, neonicotinoids in picomolar concentrations can inhibit the ACh-mediated responses in *Apis mellifera* (Cens *et al.*, 2022).

Pests can develop pesticide resistance through genetic mutations caused by the target site insensitivity. This can lead to the need for higher doses or alternative chemicals, impacting environmental and human health. Pesticides can affect non-target organisms, including beneficial insects, soil microorganisms, aquatic life, and birds. Pesticide residues can remain on food and in the environment, potentially causing health issues such as endocrine disruption, neurotoxicity, and cancer. Several in vitro studies have shown to induce genetic DNA damage in various living organisms, including humans (Pathak *et al.*, 2022).

Pesticides are also prevalent and cause toxicity in honeybees, further compromising pollination. Also, they are known to impair the functions of aquatic animals and birds and invariably alter the soil microbial communities, which are potential growth regulators to plants in the soil (Daisley *et al.*, 2022). A relevant study demonstrated that exposure of honeybees to

commercial herbicides and fungicides, alone and in combination, resulted in the activation of detoxification enzymes, affecting alkaline phosphatase activity, and even impaired learning and memory in honeybees (Di Noi *et al.*, 2024).

3.5.2 Mechanisms of agricultural chemicals in different organisms

Agricultural chemicals, commonly known as agrochemicals, include pesticides (herbicides, insecticides, fungicides), fertilizers, and growth regulators. The mechanisms by which these chemicals affect different organisms vary significantly based on the type of chemical and the target organism.

3.5.2.1 Herbicides

Herbicides are synthesized to target specific plant metabolic pathways, such as photosynthesis, plant hormone action, and cell division, killing plants in various ways. For herbicides to be effective, they must contact the site of action in the weed. Each herbicide manifests a different mode of action that affects various sites in plants. For instance, growth regulators like 2,4-D control broadleaf weeds and plants by mimicking natural hormones like auxins, which cause uncontrolled growth by disrupting the hormone balance, leading to the plant's death (Islam *et al.*, 2017). Similarly, they also inhibit shoot and root growth, affecting cell division.

Many herbicides also act as photosynthesis inhibitors, blocking photosynthesis and leading to cell membrane destruction. For example, atrazine interferes with photosynthesis by binding to the D1 protein, which further inhibits electron transport in photosystem II (Battaglino, Grinzato, and Pagliano, 2021). The herbicide glyphosate can inhibit the biosynthesis of aromatic amino acids in *Amaranthus palmeri* plants by altering the release of the plant enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) in the shikimate pathway (Zulet-González *et al.*, 2020).

Lipid biosynthesis inhibitors such as fluazifop and haloxyfop are widely used for selective suppression of grass weeds by inhibiting the acetyl-CoA carboxylase (ACCase) activity needed for lipid biosynthesis, thus preventing biological membrane formation (Liu *et al.*, 2017). Light-activated herbicides such as paraquat and diquat act as cell membrane disrupters, thus causing necrosis. In addition, specific pigment biosynthesis inhibitors, like clomazone, inhibit carotenoid biosynthesis, leading to chlorophyll destruction and photosynthesis inhibition (Lushchak *et al.*, 2018).

3.5.2.2 Fungicides

Fungicides kill, repel, prevent, or mitigate fungi to protect tubers, fruits, and vegetables during storage and growth. Their mode of action depends on their role, including contact fungicides to prevent infections, anti-sporulates to prevent spore production, and curative fungicides to inhibit spore germination and disease development even after penetration and post-infection of host tissues. Fungicides can be single-site, targeting a critical enzyme or protein, or multisite, affecting various metabolic sites.

For instance, ergosterol biosynthesis blockers (conazoles) block ergosterol synthesis in fungal cell membranes by inhibiting cytochrome P450 (CYP-51) (Hu and Chen, 2021). Protein biosynthesis inhibitors (dithranol) act as multisite inhibitors, modifying sulfhydryl groups of proteins and preventing spore germination and germ tube growth (Chatzidimopoulos *et al.*, 2022). Benzimidazoles inhibit microtubule reassembly. Azoxystrobin, known as an inhibitor of mitochondrial respiration, blocks electron transfer at the quinone site of the cytochrome bc1 complex, preventing ATP generation (Musso, Fabbrini, and Dallavalle, 2020). Dithiocarbamates like mancozeb and zineb are nonspecific, multisite fungicides that affect various biochemical processes such as antioxidant enzyme inhibition, respiration suppression, and NF-kB signaling inhibition (Ajiboye *et al.*, 2022).

3.5.2.3 Insecticides

Insecticides are toxic substances that kill insects, primarily to control pests and eliminate disease-carrying insects. Based on their mechanisms of action, insecticides can be grouped into several categories, which not only affect one or more biological systems (nervous, respiratory, and endocrine systems) but also affect water balance (Souto *et al.*, 2021). For instance, nerve and muscle targets include cholinesterase inhibitors like carbamates and organophosphates, which inhibit cholinesterase activity, leading to overstimulation, paralysis, and death of the insect nervous system (Araújo, Castanheira, and Sousa, 2023). Acetylcholine receptor stimulators such as neonicotinoids and spinosad mimic acetylcholine, and binding to its receptors causes prolonged stimulation and eventual death.

Chloride channel regulation mechanisms involve avermectin activation, GABA receptor inhibition, and GABA-gated chloride channel agonists. Different species models exhibited varying effects at different concentrations of avermectins, such as quick irreversible inhibition of inhibitory postsynaptic potential in the nerve of crustaceans, elevated chloride ion

entry, blocking of signal transmission in *Ascaris,* disabling of nematodes devoid of hypercontraction, and many more (Batiha *et al.*, 2020).

Sodium channel modulators, including pyrethrins and pyrethroids, bind to sodium channels, keeping them open and causing prolonged tremors and prostration (Silver *et al.*, 2014). Many insecticides also interfere with the hormone production needed for the growth and metamorphosis of several pests, eventually preventing chitin synthesis, leading to death during early life stages, and altering the endocrine system.

3.6 Technological advances in pesticide and waste management

The background of agricultural and environmental sustainability has faced tremendous transformation due to technological expansion in pesticide and waste management (Boudh and Singh, 2018). The consistent rise in global populations and environmental issues mandates adopting innovative technologies crucial for addressing the two-fold challenge of enhancing agricultural productivity while encountering ecological damage. The technical innovation will pave the way for reforming traditions in pesticide application, waste management, and overall environmental operation (Juyal, 2024). One of the most prominent advancements in pesticide management is the initiation of precision agriculture. This modern approach utilizes GPS technology, remote sensing, and data analytics to amend pesticide use, minimizing environmental concerns and costs (Singh *et al.*, 2021b). The precision agriculture approach minimizes overapplication and surplus, diminishing the risk of contaminating surrounding ecosystems. Specifically, with the introduction of drones and autonomous vehicles equipped with sophisticated sensors in the agriculture sector, farmers can target specific areas with defined amounts of pesticides, ensuring the least waste and the highest efficiency. This targeted approach not only preserves the resources but also shelters beneficial insects and diminishes the possibility of pests developing resistance (Karunathilake *et al.*, 2023).

3.6.1 Innovations in pesticide formulations and waste treatment technologies

In the past several decades, pesticide formulations have undergone considerable improvement to improve efficiency and minimize environmental crashes for safeguarding human health (Ansari *et al.*, 2021). These developments include the progress of biopesticides, nano-formulations, and slow-release formulations, each contributing to more sustainable agricultural practices. Biopesticides are derived from natural sources including animals, plants, microbes (e.g., bacteria, fungi), and certain minerals. They tend to cause fewer environmental risks when compared to traditional pesticides (Fenibo, Ijoma, and Matambo, 2022). Their biodegradable nature with minimal residues decreases soil and water contamination. They can be target-specific, reducing non-target collisions and, therefore, may preserve the soil-beneficial insects (Zheng and Xu, 2023). For instance, *Bacillus thuringiensis* (Bt) produces toxins that are injurious to specific insects, and neem oil disturbs the life cycle of certain pests. Integrated pest management (IPM) systems collaborate biological, physical, chemical, cultural, and cultural tools to formulate more holistic biopesticide formulations for feasible pest control approaches (Angon *et al.*, 2023). Such formulations have enhanced the stability, shelf-life, and effectiveness of biopesticides. Examples include microbial pesticides, plant extracts, and pheromones interrupting pest mating behaviors (Butu, Rodino, and Butu, 2022). Further, by implementing natural predators, crop-rotation systems, and other ecological principles, IPM decreases the dependence on chemical pesticides and encourages long-term agricultural well-being. Advancements in nanotechnology have led to the creation of nano-formulations, sometimes termed nano-pesticides, which represent another significant innovative approach in the agricultural industry (Behl, Jaiswal, and Pabbi, 2024). Nano-pesticides utilize the application of nanoparticles to encapsulate the active ingredients, which enhances the stability, solubility, and bioavailability of pesticides. Furthermore, the small size of nanoparticles enables the active ingredients to penetrate deep into the pest cuticles effectively and remain active longer, thereby improving the efficacy and reducing the number of applications needed (Saranya *et al.*, 2020). Similarly, encapsulation techniques, such as microencapsulation and nanoencapsulation using biodegradable polymers, shelter the active ingredients of pesticides from natural degradation and allow their steady release over time (Kumar *et al.*, 2024). This approach minimizes the need for frequent applications and encounters the risk of pesticides leaching into water bodies. Additionally, combining multiple active ingredients with balancing modes of action in a single formulation can improve pest control and diminish the probability of resistance development. Synergistic formulations can target various pests concurrently and offer broader-spectrum protection (Pertot *et al.*, 2017).

In waste management, technological modernizations play an essential role in transforming agricultural waste, especially pesticide residues, diminishing the associated health risks (Singh *et al.*, 2021a). One of the most common practices is the expansion of bioremediation techniques, which use microbial agents or their enzymatic machinery to

degrade pesticide residues in soil and water. These bio-agents are capable of metabolizing the pesticides by breaking or transforming them into less toxic and harmful compounds (Baite *et al.*, 2024). Further, advanced genetic engineering approaches are currently being employed to enhance the efficiency of these microbial communities, facilitating them to degrade or transform a broad spectrum of pesticides more precisely (Thakur *et al.*, 2023). Another modern technology is the implementation of photo-catalysis, where light-activated catalysts guide and accelerate the degradation of pesticides. For instance, titanium dioxide (TiO_2) is a commonly employed photo-catalyst. TiO_2, when exposed to UV light, generates ROS (reactive oxygen species), which decomposes the pesticide molecules (Akakuru *et al.*, 2020). This modern approach can be adopted for water treatment systems to degrade pesticide residues from agricultural runoff, protecting marine ecosystems.

Similarly, adsorption techniques using biochar, activated carbon, and zeolites have also been developed to eliminate pesticide residues from water bodies (Bose *et al.*, 2023). These materials' high surface areas and porosity enable the effective adsorption and immobilization of pesticide molecules. This practice is predominantly helpful for treating contaminated water bodies and preventing the spread of pesticides into the holistic environment (Ponnuchamy *et al.*, 2021).

3.6.2 *Impact of new technologies on reducing environmental and health risks*

The induction of novel approaches in pesticide formulations and waste treatment has an intense impact on reducing environmental and health risks. These technologies enhance the accuracy and efficacy of pesticide applications, simultaneously diminishing the adverse effects on non-target organisms, the environment, and human health.

Advanced agriculture technologies, viz., GPS-guided sprayers and drone-based applications, play a central role in reducing pesticide tradition. These technologies facilitate farmers to be concerned with pesticides only where needed, curtailing overapplication and off-target flow. GPS-guided sprayers certify precise assignment of pesticides, tumbling the risk of contamination in non-target areas. The drone-based application presents accurate and targeted spraying, principally in hard-to-reach areas, enhancing pest control while lowering environmental impact (Kasenzu, 2024); likewise, IPM strategies sustained by advancements in monitoring and decision-support tools also diminish environmental and health risks. Modern practices, including field sensors, remote sensing, and predictive modeling, offer real-time data on pest populations and environmental conditions, helping farmers decide on pest control measures (Tonle *et al.*, 2024).

Further, the development and implementation of biopesticides and bio-based formulations have drastically lowered the environmental footprint of pest management. The exercise of bio-based formulations supports sustainable agricultural traditions and curtails the dependency on synthetic chemicals (Baite *et al.*, 2024). Innovative formulations and slow-release strategies have improved the safety outline of pesticides. The slow and gradual leaching of active ingredients lowers the frequency and quantity of pesticide applications, minimizing the risk of exposure to non-target beneficial organisms and human health. Moreover, encapsulation practices shelter active ingredients from environmental degradation, ensuring that pesticides remain efficient for extended phases and reducing the demand for repeated applications (Kalyabina *et al.*, 2021).

On the other hand, waste treatment technologies, such as bioremediation and photo-catalysis, efficiently tackle the issue of pesticide residues in the natural environment. Bioremediation utilizes wild or genetically engineered microorganisms or their enzymatic machinery to break pesticide residues into less harmful compounds (Giri *et al.*, 2021). This approach not only disinfects the contaminated place but also barricades the spread of pesticides to adjacent sites. Likewise, applying light-activated catalysts in photo-catalysis reduced the pesticide molecules in water and the risk of contamination in marine ecosystems (Akakuru *et al.*, 2020). The induction of advanced monitoring and detection systems advances the facility in managing pesticide-related risks. Technologies such as biosensors and remote sensing platforms facilitate real-time detection of pesticide remains in soil and water ecosystems. The data generated by these advanced technologies may contribute to better knowledge, management of pesticides, and policy development (Mutunga, Sinanovic, and Harrison, 2024).

3.7 Conclusion

Agricultural pesticides, herbicides, fungicides, and various chemicals are exerting severe effects on the ecosystem. Many organisms are affected by different pesticides and chemicals as they are biomagnified after consumption periods. Studies indicate that pesticides and nano-fertilizers are highly fatal for aquatic organisms. Some technologies and management processes are flourishing nowadays. However, much research is required to implicate those technologies at the ground level with the most efficient proficiency to attenuate the redundancy of different types of agro-pesticides and chemicals.

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Chapter 4

Nutrient, fertilizer, and plastic waste in the agriculture sector

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Chapter Outline

4.1. Introduction 49
4.2. Current scenario of fertilizer and plastic use in agriculture 50
4.3. Waste and its classification 51
4.4. Nutrient, fertilizer, and plastic waste 52
4.5. Waste to wealth 57
4.6. The prospect of agricultural waste management 58
4.7. Conclusions 58
References 58

4.1 Introduction

The sustenance of human beings on Earth largely depends on the availability of essential life requirements like nutritious food, clean water, fresh air, etc. The role of proper nutrition and a healthy environment (soil, water, and air) cannot be neglected if we aim to promote a sustainable and healthy living environment. Agriculture and other allied sectors have a key role in maintaining soil, water, and the environment. A sustainable living environment can only be achieved through environment-friendly improved agricultural practices/techniques. During the Second World War, enhanced agricultural production gained more importance in ensuring the population's food security (Food and Agriculture Organization of the United Nations, 1948). Therefore, the agriculture sector gained significant importance in enhancing food security and livelihood and was prioritized to reduce poverty and malnutrition. The subsequent surge in population demanded more food and livelihood security, necessitating increased agricultural production by applying fertilizers, agrochemicals, and advanced scientific management practices (FAO & Organization for Economic Co-operation and Development, 2019).

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According to the UN reports, by 2050, around two-thirds of the population will reside in urban areas. The rural population is estimated to be reduced by about 200 million, increasing the population in cities and towns by around 2.4 billion. Urbanization will lead to changes in food consumption patterns and demand for more diversified food, simultaneously leading to shrinkage of the arable land; hence, the gap between production and demand is estimated to increase in the future. Large amounts of solid, liquid, or gaseous wastes are generated depending on the stages involved in production and processing techniques in agricultural sectors. To mitigate the negative impact of these wastes, we should have comprehensive knowledge about them (their sources, handling, treatment, management, etc.). The generation of solid agricultural wastes is increasing every year, with an annual rate of about 7.5% (Wang *et al.*, 2021).

The indiscriminate dumping of these wastes has resulted in soil contamination as well as air and groundwater pollution, threatening the environment and aquatic ecosystem (Karak *et al.*, 2015). The shift in animal production systems to fit the market demand has also led to soil and water contamination due to animal drops and urine containing pathogens and organic chemicals (Kumar, Shahi, and Singh, 2018). High-analysis chemical fertilizers and organic residues, an integral part of the agricultural production system, can threaten human health and environmental sustainability, if not uesd properly (Meena *et al.*, 2020). Therefore, the proper scientific management of these chemicals and nutrients can shape the solution to mitigate the adverse environmental effects (Sinha *et al.*, 2022). In this era of modern agriculture, proper use of plastic and its disposal also plays a significant role in attaining sustainable goals (Hofmann *et al.*, 2023). They are used in various agricultural activities like mulching, protected cultivation systems (poly houses), seedling trays, irrigation systems, fertilizers, and pesticide containers (Hachem, Vox, and Convertino, 2023). The deposition of untreated plastic waste in soil and water can adversely impact aquatic life, soil ecosystem, and environmental sustainability. Therefore, the prime objective of this chapter is to understand agricultural wastes and their categorization, focusing mainly on the nutrients, fertilizers, and plastic waste generated by the agricultural sectors. The chapter also briefly covers their fate, recent status, and management strategies, which can lead to their effective handling and management to reduce their negative environmental impacts.

4.2 Current scenario of fertilizer and plastic use in agriculture

The fertilizer manufacturing industry is a vital sector in terms of investment, and the turnover is also very high. After the Green Revolution, the consumption of fertilizer witnessed a higher spike, but it varied among countries, states, and regions (Roy and Mondal, 2023). On average, in 1970−71, fertilizer consumption was 2.26 Mt, which increased to 28.97 Mt in 2019−20 in India (Shukla *et al.*, 2022). Therefore, total fertilizer consumption in terms of N, P, and K was observed to be second in the world (28.97 Mt) after China (52.50 Mt) (FAOSTAT, 2012). There is a prevalence of higher consumption of N fertilizers in comparison to other macronutrient-based fertilizers, and according to a study by Galloway *et al.* (1995), the extrapolation of the trend in the use of N fertilizer revealed an increase of 2.5% per year for countries that are less developed. Studies also suggest that N fertilizer consumption in India increased 13 times from 1970 to 2020. India's phosphorus consumption trend (over 40 years) varied from 0.54 Mt during 1970−71 to 7.28 Mt in 2010−11 (14 times). On the other hand, relatively lesser consumption of K was observed at 0.24 Mt in 1970−71 and increased to 2.64 Mt in 2019−20, which is almost 11-fold. Studies by Watson, Kaerwer, and Martin (2015) revealed that the country's economic development also leads to an increase in the consumption of fertilizers. For developing countries, the consumption may rise to 2.3% per year from 1990 to 2025. The International Fertilizer Association (IFA) reported that approximately 120 million tons of nitrogen and 45 million tons of phosphorus fertilizers are used globally. Given the inefficiencies, this translates to

TABLE 4.1 Estimated average N and N,P,K use in the years 2010 and 2025 in developing countries.

Nutrients/year	2010	2025
NPK*	123	169
N	78	106
#N use/ha	93	121

**NPK use in million tons.*
#kg N/ha.
From Bouwman, A.F. & Van Der Hoek, K.W. (1997). Scenarios of animal waste production and fertilizer use and associated ammonia emission for the developing countries. Atmos. Environ. 31(24), 4095−4102. https://doi.org/10.1016/s1352-2310(97)00288-4.

TABLE 4.2 Estimated global annual quantities of plastic use in agriculture.

Plastic products	Quantity (million tons)
Greenhouse films	3.5
Mulch films	2.5
Silage films	1.4
Non-films (pipes, nets, etc.)	2.5
Pesticide containers	0.3
Tree guards	0.2
Fertilizer coatings	0.1

From FAO. (2021). Assessment of agricultural plastics and their sustainability: a call for action. FAO, Rome, Italy. https://doi.org/10.4060/cb7856en.

roughly 60–72 million tons of nitrogen and about 20 million tons of phosphorus fertilizers potentially being wasted annually.

Since the rise of plastic production, their use has been prevalent worldwide in the day-to-day activities of life (Kim, Ahn, and Cha, 2022). The success of plastic can be attributed to its properties such as durability, low price, light weight, and ease of handling. In addition to that, plastics can be molded into desired shapes and converted to useful forms very easily (Vox *et al.*, 2016). No alternative is available in the market with this wide range of desired properties and manageability. These qualities have made it suitable for various sectors and purposes, including crop production and packaging. In 1950, the production of plastic was almost zero, but gradually it increased and reached 348 Mt in 2017 worldwide. Asia produces more than half of the plastic used worldwide and is the biggest producer. China has a global contribution of 29% and the highest share in the process of plastic production, and it is estimated that the figure can surpass 500 Mt by 2050 (Sardon and Dove, 2018). Covering the soil surface with plastic mulch in agriculture is common in many countries. In Europe, almost 4270 km^2 of agricultural surfaces are estimated to be covered by plastic film (Scarascia-Mugnozza, Sica, and Russo, 2011). The covering rate of agricultural surfaces in China increased by 30% per year between 1991 and 2004 (Espí *et al.*, 2006). Plastic itself is not harmful, but its long-term deposition in the environment can adversely affect the natural agro-ecosystem. That is because when plastics are left untreated for a long time, they may hurt human health and the ecosystem. In the future, with the intensification of agriculture, the use of plastic is likely to rise at an alarming rate (Espí *et al.*, 2006). Therefore, by examining the trend of the fertilizer and plastic wastes generated during agricultural commodities' production and processing, it is necessary to assess the importance of its proper management and treatment to avoid or reduce the adverse impact.

4.3 Waste and its classification

Waste from agriculture (agricultural waste) is a product obtained during the production, processing, and packaging of agricultural produce like grains, vegetables, fruits, dairy products, meat, and poultry. These are termed waste because their collection, processing, and transportation expenses are much higher than their economic value. They include different types of materials like plant residues (straw, bran, husk, stalk, bagasse, etc.), dairy waste (urine, bedding materials, dung or excreta, carcasses, etc.), food-processing waste (skin, seeds, kernels, etc.), and toxic agricultural waste (herbicide, pesticide, insecticides, etc.) (Obi, Ugwuishiwu, and Nwakaire, 2016). Wastes in the agriculture sector are mainly classified into organic or synthetic based on their origin (Figure 4.1). Organic wastes include plant residues, livestock, fruit, and vegetable wastes. Meanwhile, synthetic wastes comprise agrochemicals, excessive fertilizers, and disposed plastics. A significant portion of agricultural waste can also be from slurries and liquids from crop production, agro-industry, and livestock production (Obi, Ugwuishiwu, and Nwakaire, 2016).

4.3.1 Crop/harvest waste

Generally, organic residues can be broadly classified into two broad categories: one that remains in the field after harvesting the crop, like leaves, stalks, seeds, and stems, and the other obtained after processing, like molasses, bagasse, seeds, shells, and husks. On average, annually, there is a production of 731 Mt of rice straw (Sarkar *et al.*, 2012), 354.31 Mt of

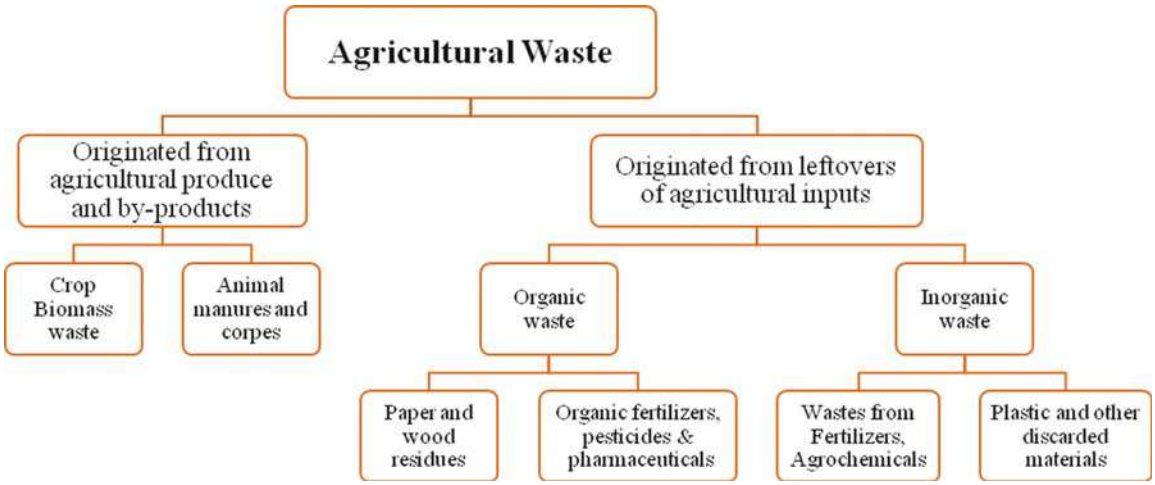


FIGURE 4.1 **Different types of agricultural wastes.**

wheat straw, and 128.03 Mt of maize stover (Pattanaik *et al.*, 2019). The portions left over after extraction of economical parts from jute, sugarcane, sorghum, oats, and barley are also included in the category of agricultural waste. The annual total crop residue production in the world is almost 2802 Mt (Zabed *et al.*, 2016), and the waste derived from fruit and vegetables is around 50 Mt globally (Hardia, 2015). The type and amount of generated waste depends on the crop management, location and climatic condition of that particular area (Obi, Ugwuishiwu, and Nwakaire, 2016). In developing countries, very high amount of fruit and vegetable waste are generated due to a lack of storage and processing facilities. Most losses occur during the harvesting and consumption stages (Esparza *et al.*, 2020).

4.3.2 Agro-industrial waste

The byproducts that are produced in food processing industries include waste after fruit extraction, peels of fruits and vegetables, sugarcane bagasse, deoiled cakes, molasses, animal skin, slaughter house waste, meat processing wastes, etc. (Pattanaik *et al.*, 2019). The significant wastes generated in agro-industries are sugarcane bagasse (180.73 Mt) and palm oil waste (35.19 Mt) (Sukiran *et al.*, 2017; Yadav *et al.*, 2020). Various effluents generated from these agro-industries and food processing industries are also considered waste and cause considerable adverse effects on human health and the environment.

4.3.3 Livestock wastes

Livestock and poultry industries generate waste mainly in the form of solid and liquid. The composition of these wastes depends on the composition of the diet, size, and age of the animal (Ryser *et al.*, 1994). The waste generated from these industries can cause harm to the environment if left untreated. Solid waste can release about 18% carbon dioxide and 37% methane, potential greenhouse gases contributing to global climate change (Holm-Nielsen, Al Seadi, and Oleskowicz-Popiel, 2009).

4.3.4 Hazardous wastes

Large quantities of artificial or non-natural wastes are generated in agriculture sectors at the production and processing levels. The synthetic inputs required at the agricultural production and processing levels, such as machinery, equipment, plastic containers, and agrochemicals, including fertilizers and animal health products, also contribute to soil, water, and air pollution if they are not disposed of and treated correctly after use. Even reckless disposal of animal health products, plastic waste, and agrochemicals can cause long-term adverse effects on human health.

4.4 Nutrient, fertilizer, and plastic waste

4.4.1 Sources

Nutrients and fertilizers entering our ecosystem as pollutants may come from different sources, *viz* points, non-point, or diffused sources. Point sources are generally more accessible due to their specificity, whereas non-point sources are

multiple in number and are difficult to identify. Diffuse sources cannot be identified as they involve many sources in releasing contaminants into the environment (Gozzard *et al.*, 2011). The major nutrients that cause contamination of water bodies and soil systems mainly originate from fertilizers, followed by manures. This, in turn, enters into our food system and gets deposited in human and animal bodies. As a part of the vicious loop, the fertilizer residues again enter the soil and water as contaminants through excreta and carcasses. According to Boers (1996), diffuse sources such as the leaching of nutrients from agricultural lands hold far more relevance than any other point sources. The most widely used fertilizer as per plant requirement is nitrogenous fertilizers, followed by phosphatic fertilizers (Bouwman and Van Der Hoek, 1997). The excess amount of fertilizer and manures is applied to achieve more yield and is the primary cause of loss of nutrients from agricultural fields, which pollutes the soil and water bodies mainly through surface and sub-surface runoff and leaching. Nitrogen from organic matter can be released by mineralization, and released nitrogen undergoes denitrification, which further adds to environmental pollution (Roy and Mondal, 2023). The nutrient cycle in soil consists of the release and fixation of nutrients simultaneously, and there is some irreversible fixation of soil nitrogen and phosphorus and then accumulation. However, these are all finite fixation processes, and an overdose of these nutrients surpasses their capacity, resulting in their release into the environment. Excess amounts of these nutrients lead to pollution and are considered as waste.

In agricultural sectors, vast quantities of polyethylene film are used for diverse activities like mulching, net house preparation, and water harvesting structures etc. (Figure 4.2). Various plastic substances are also used in packaging agrochemicals, agricultural products, etc. When these materials are not disposed of properly, they become a threat to the environment and are considered waste. These materials undergo degradation processes, either biotic (microbial actions) or abiotic (various environmental factors), but these degradation processes can take hundreds of years and can be considered to be inert in the natural environment. Studies have revealed that the accumulation of plastic waste in landfills and in the open air will be nearly 12,000 Mt by the middle of this century if the rate of production and disposal remains the same (Geyer, Jambeck, and Law, 2017). According to Steinmetz *et al.* (2016), there was a four-fold increase in the use of plastic for mulching from 319 to 1245 megatons between 1991 and 2011. Therefore, agricultural sectors dispose of a considerable amount of plastic waste in the environment, which can be obtained from both point and non-point sources. Therefore, it is essential to have an extensive understanding of their chemical nature and impact on the ecosystem for better handling and treatment.

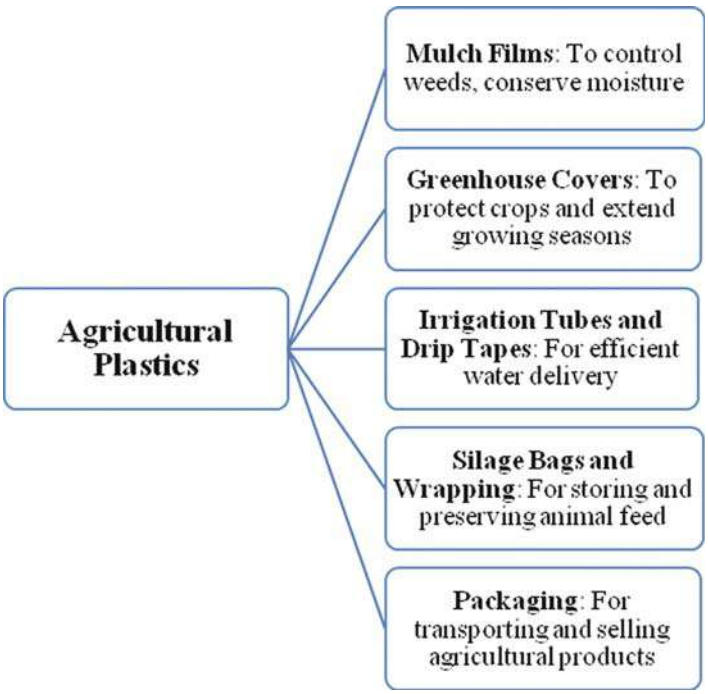


FIGURE 4.2 **Use of plastic in agriculture.**

4.4.2 How and why are they considered waste materials?

The loss of fertilizers and nutrients from agricultural fields is unavoidable even after setting specific limits under different approaches. The losses can be reduced but cannot be stopped entirely. For instance, irreversible phosphorus sorption, phosphorus fixation, denitrification of nitrogen, and leaching of nutrients from organic manures and fertilizers are very difficult to control. The only identifiable solution is that fertilizers should be applied according to crop uptake or demand (Oenema and Dijk, 1994). The phosphorus adsorption by soil has proven to be a time bomb in preventing eutrophication in water bodies. The fate of soil phosphorus mainly depends on the soil sorption capacity, which, in turn, depends largely on the concentration of ferric hydroxides and the presence of amorphous aluminum in the soil. The excessive fertilizers remaining in the soil and not taken up by the crop are finally washed into groundwater. The depth of groundwater and soil characteristics influences the fate of loosed fertilizer or nutrients.

The release of organic contaminants from intensive livestock farming can have far-reaching economic consequences from an environmental perspective. The limited amount of land available for the construction of farms and the disposal of farm waste, dung, and other cattle wastes results in mismanagement in handling and disposal. The organic wastes derived from the livestock sector can be used as manure if appropriately processed. Different types of plastic waste are generated from the agricultural sector. Due to the degradation of large-sized plastic waste, there is deposition of fragments of smaller bits, which can be called particulate plastics. These smaller bits can be further divided into microplastics (less than 5 mm) and nano-plastics (less than 0.1 mm) (Li *et al.*, 2021). Studies showed that microplastic pollution in soil systems could cause toxicity to the entire ecosystem and can also affect the soil properties (Wang *et al.*, 2020). According to the study by Hadad, Geresh, and Sivan (2005), the biodegradation of plastic waste by a specific microbial strain, after 10 years when incubated into the soil and exposed to UV radiation, only less than 0.5% of polyethylene underwent degradation. Hence, plastic waste must be appropriately managed to create a safer environment.

4.4.3 Problems associated with them

The application of nitrogenous fertilizers to achieve good yield is a common practice worldwide; however, excess or injudicious application of the same results in the accumulation of nitrogen in different forms in soil and water. The loss of excess nitrogen occurred through different processes *via* leaching, denitrification, etc. The evaporation of water in arid and semi-arid areas, where crop growth is dependent on irrigation water, shows the enhanced nitrate concentration in the soil. Depending on management practices and prevailing climatic conditions, there is a varying amount of nitrate leaching and accumulation at different soil depths. Fertilizers are converted to nitrate by the process of nitrification mediated by microorganisms. Studies revealed that, despite prevailing ideal conditions, plants absorb approximately 50% of nitrogenous fertilizers (nitrogen) applied to the soil. The remaining 2−20% is lost through volatilization, 15−25% reacts with organic compounds in soil clay, and 2−10% contaminates the soil and groundwater. Nitrate, the basic component of nitrogenous fertilizer, is mainly responsible for water pollution by leaching, seepage, and surface and sub-surface runoff. Nitrogen can also be present in nitrite, dissolved nitrogen, nitrogen oxide, and organic nitrogen (Savci, 2012). Eutrophication is a common problem in water bodies and is mostly prevalent due to overusing of fertilizers. With the increase of nutrients like nitrogen and phosphorus in water bodies, there is a sudden increase in algae and other aquatic plants, which causes deterioration in water quality due to higher oxygen demand. As a result of eutrophication, an anaerobic condition is created in the bottom layer of water bodies, which kills many aquatic inhabitants, produces odor, and turns the water unfit for human consumption. Moreover, the high nitrate concentration in soils subsequently enhanced nitrate concentration in plants and animals, which is harmful to human health as it finally accumulates in the human body along the food chain (Sonmez *et al.*, 2008). The nitrate in water is absorbed by the intestinal tract in 4−12 hours and is eventually excreted by the kidneys. The salivary gland can also deposit nitrate by various mechanisms. In an anaerobic environment in the digestive tract, the nitrate is reduced to nitrite. The toxic effects of nitrates on the human body can be further understood in three stages. Inflammation can be seen in the digestive and urinary tracts when drinking water contains more than 50 mg/L of nitrate. In infants, high nitrate concentration causes the condition of methemoglobinemia, in which the hemoglobin in the blood loses its capability to bind with oxygen due to the presence of nitrate. As a result, the oxygen transport function of the blood is lost, which causes the death of the infant. Due to the presence of stomach acids in adults, there is the formation of secondary and tertiary amines, tertiary nitrites, nitrosamines, and alkyl ammonium bases, which have strong carcinogenic properties (Savci, 2012). As soils have strong buffering capacity, the adverse effects of synthetic fertilizers and other agrochemicals are not obvious immediately after they are released. However, with time, the overdose of fertilizers leads to soil pollution and deterioration (Roy *et al.*, 2021). In addition, the toxins from chemical substances accumulate in vegetables and fruits, which enter the human and animal body and cause a negative impact on their health. Chemical compounds like ammonium nitrate, sodium nitrate, potassium chloride, potassium sulfate, and ammonium

chloride can destroy the soil structure, make the soil unfit for cultivation, and reduce productivity. Applying acid-forming nitrogenous fertilizers can lead to soil acidity, decline in soil pH, and a reduction in crop yield. Using excess basic fertilizers can also cause adverse effects by increasing the soil pH and causing significant loss in crop yield. Nitrogenous fertilizers can cause air pollution through nitrous oxide and nitrogen dioxide emissions. Other gases mainly responsible for the warming of the atmosphere are methane, carbon dioxide, hydrogen sulfide, and chloro-fluoro hydrocarbons. All these phenomena are responsible for global warming. Degradation of plastic in the environment releases several secondary pollutants, including volatile organics, which threaten to contaminate the groundwater (Kaplan *et al.*, 1996). The plastic substances on degradation produce smaller-sized microplastics, which pose a threat to food production. Therefore, in order to manage the residues from plastic, it becomes imperative to identify their source. The contaminated plastic substances used in mulching or other agricultural activities are not even suited for landfilling as they pose the risk of pesticide leaching (Wang *et al.*, 2013). Moreover, polyethylene sheets can act as a medium for the transference of pesticides in the soil by the process of absorption of pesticides in the non-crystalline areas of the film (Huckins *et al.*, 1993; Nerín *et al.*, 1996) and, after that, releasing the absorbed pesticides in the soil matrix (Ramos *et al.*, 2015). When polyethylene and polyvinyl chloride is incinerated at high temperatures of about 1000°C, they release polycyclic aromatic compounds and ozone-damaging greenhouse gas, carbon dioxide, which is also lethal to human health (Wang, Vinocur, and Altman, 2003; Wang *et al.*, 2013). When burned in open conditions, plastics can release up to 20 times more carcinogenic dioxins and 40 times atmospheric particulate matter than incineration in controlled high temperatures (Levitan and Barros, 2003). Therefore, the handling and disposal of these wastes must be planned carefully to reduce the further negative impacts due to their mismanagement.

4.4.4 Reason for mismanagement

The widespread and injudicious use of synthetic fertilizers and nutrients to enhance production and productivity is shared across countries worldwide. However, a considerable gap in knowledge exists between the essentiality of the nutrients and the optimum amount required for crop growth. This disparity in understanding is the main cause of considerable economic loss and the negative impact of these synthetic fertilizers on our ecosystem. When farmers apply these fertilizers and nutrients or use any plastic substances in the production and packaging process, they only focus on the immediate outcome: the profit fetched by the produce. Without proper awareness, applying nutrients and fertilizers often exceeds the required amount. That is mainly because of the lack of proper knowledge about balanced fertilizer and nutrient application and the crops' optimum use of the fertilizer to increase production. The plastic substances used in packaging various products, mulching, or construction are also dumped near fields after use, where they get mixed with the soil releases lethal compounds. This mishandling of fertilizers, nutrients, and plastics usually results from poor knowledge about their possible pathways in the environment and the probable damage they can incur to human and animal bodies or the entire ecosystem. Therefore, initiatives must be taken to provide practical training to farmers or users and make them aware of the significance of proper handling and disposal of these agricultural wastes. A clear notion must be given about the close relationship between environmental safety, sustainability, and food security. The implication of proper guidelines from the farmer field to the treatment and recycling units must be strengthened to ensure safety and minimize economic loss. Experts should closely observe the application of fertilizers in the required quantity and at the right time to reduce the risk of overuse of fertilizers. Sometimes, an inclination toward age-old indigenous practices can also make farmers reluctant to recognize the importance of safe disposal of farm waste. Moreover, in many parts of the world, the absence of proper disposal systems from farmers' fields to treatment units is the main reason behind the reckless dumping in soil. The disposal of plastic substances is very labor-intensive and costly, especially those used in mulching and buried in the agricultural field (Steinmetz *et al.*, 2016). Even if they are segregated from the field, they remain contaminated with soil and agrochemicals, which causes problems in their proper disposal and recycling (González-Sánchez *et al.*, 2014).

4.4.5 Management of waste materials

4.4.5.1 Management techniques to reduce nutrient loss

The nutrients required by the crops to produce optimum yield can be availed to them either in the form of synthetic fertilizers or organic manures, composts, green manure crops, etc. The management of excess fertilizers and nutrients that leach from agricultural fields can be achieved with certain principles involved in applying and using fertilizers. Selecting proper fertilizer sources helps easy application and reduces the cost per unit area. For instance, when a controlled-release nitrogen source is applied to the field, it delivers nutrients in small quantities, but the release continues throughout the growing period as per the crop demand. On the other hand, soluble synthetic fertilizers provide nutrients to the plants only for a short period, and the excess amount of fertilizers is washed away with irrigation water and pollutes the soil and water

through leaching or seepage. Manures should also be considered a good source of nutrients as they also ensure the availability of small amounts of nutrients throughout the growing period. Therefore, integrated approaches must be adopted to supply nutrients. However, in order to apply the correct quantity of fertilizers for optimum crop growth, soil testing should be carried out to determine the status of available soil nutrients (Hochmuth, Mylavarapu, and Hanlon, 2015) and apply the nutrients accordingly. Basic information about soil fertility status can assist in making proper fertilizer recommendations. The amount of fertilizer required for a particular crop also depends on the variety, location, climatic conditions, etc. As the nutrient requirement of the crop changes depending on the crop growth stage, the determination of the right time for applying fertilizers is also essential for the optimum use of nutrients and minimizing the loss. The proper placement method is also very important to ensure maximum nutrient availability to roots and reduce the loss of nutrients by leaching. The placement of the nutrients must be near the root zone, where the plants can have the maximum absorption of the nutrients (Hochmuth, Mylavarapu, and Hanlon, 2015).

4.4.5.2 Use of clay minerals

The clay materials contain a relatively huge amount of negative charges and cation exchange capacity (CEC). Smectite or montmorillonite clay minerals have a high charge density and CEC. Depending on their genesis, these clay minerals remain saturated with calcium, magnesium, sodium, potassium, and other minerals. This artificially extracted bentonite clay can also be used as a medium to deliver plant nutrients in a controlled way (Singh, 2017). Hydrocalcites can also be used as a medium for supplying anionic plant nutrients like N, P, and S. They can be easily synthesized and can have a long lifespan in soil. Therefore, the crop's requirements can be fulfilled by supplying these nutrients to the soil with the help of clay minerals. This will reduce the loss of nutrients and improve the fertility status of the soil, as well as nutrient uptake and nutrient use efficiency (Gillman and Noble, 2005).

4.4.5.3 Recycling of plastic wastes

One of the important and cost-effective way to manage plastic waste is recycling. It involves collecting plastic wastes and converting them into raw materials that can be reused to form other valuable products. Recycling is also synonymous with terms like renewing or reusing to prevent the damage caused to human health and the environment. Plastics are nonbiodegradable carbon polymers that can be melted and shaped into other valuable products. The process can include different steps, such as washing, shredding, identifying, separating, and compounding. Incineration or burning of plastic waste can have adverse impacts on the atmosphere due to the release of harmful gases into the environment, which can be avoided by recycling (Shen *et al.*, 2016). Therefore, recycling assists in achieving sustainable goals and enhancing environmental sustainability. The process can also release some volatile gases, organic fumes, and ashes that can adversely affect the environment (Shen *et al.*, 2016). After certain rounds of recycling, the plastic substances become unfit for further recycling process and eventually end up in landfills. They are not further considered secondary unconsumed plastic waste (Zheng, Yanful, and Bassi, 2005).

4.4.5.4 Incineration of plastic wastes

The process of burning wastes in the presence of oxygen is called incineration. In this chemical process, the substances' complete combustion ultimately releases carbon dioxide and water vapor into the atmosphere (Shen and Worrell, 2014). Some plastics are also resistant to combustion and have explosive properties. Therefore, carefully selecting the plastics is the key to avoiding unexpected explosion incidents. The incinerated substance mainly comprises hydrochloric acid, ash, and volatile chemicals. Combustion of organic molecules can also provide us with fuel and contribute to reducing waste deposition. This process can generate electricity from biomass in the form of renewable energy, which is essential in modern industrialization. This process also helps decrease transportation costs, destroy harmful microorganisms, etc. The limitations of this process are the suitable land requirement, the expenses required to set up a plant, and the waste management procedures that must be followed (Netzer, Li, and Løvås, 2021).

4.4.5.5 Landfills

The plastics that are discarded after use and thrown away are finally deposited and accumulated in landfills. These are the areas where plastics are dumped before burying them in the soil after their utilization. Precautionary measures are very important in this process because their mishandling can cause soil degradation and contamination of groundwater (Zheng, Yanful, and Bassi, 2005). The process's main objective is to safely dispose of plastic waste and prevent it from polluting the aquatic and soil systems. Depending on the composition of its polymer, the plastic waste takes various time spans in its

biodegradation, which may vary from ten to hundreds of years (Thiounn and Smith, 2020). Landfills can also serve as a source of energy because the biodegradation process releases carbon dioxide and methane if managed properly.

4.4.5.6 Pyrolysis

Pyrolysis can be defined as the process of conversion of gases and fatty oils to hydrocarbons to recover crude petrochemicals. The crude petrochemicals recovered from the pyrolysis of plastics may act as a renewable energy source. Most plastic products used in packaging are thermoplastics, and they can reform their molecular structure and are susceptible to change (Nabi *et al.*, 2021). The crude oil derivatives of plastics are converted into monomers like additives and plasters (Shent, Pugh, and Forssberg, 1999). Therefore, pyrolysis is a good management practice that allows plastic waste to be converted into useful products scientifically.

4.4.5.7 Bioremediation

Bioremediation involves detoxifying, decontamination, and degrading compounds by living organisms like fungi, algae, bacteria, and plants (Asgher *et al.*, 2020). The process occurs when the optimum concentration of nutrients and enzymes along with suitable environmental conditions like temperature, moisture, and pressure are present (Asgher *et al.*, 2020). Extracellular enzymes help in the biodegradation of these plastic polymers in plastic wastes, and in the process of bioremediation, enzymes act as a catalyst that reduces the activation energy and assists in the conversion of substrates into products. The enzymes involved in this process are microbial oxidoreductase, oxygenase, peroxidases, lignin peroxidases, hydrolases, and lipases (Jaiswal, Sharma, and Shukla, 2020; Qamar *et al.*, 2021). When plastic wastes containing polyvinyl chloride degrade naturally, they release monomers like vinyl monomers, chlorofluorocarbons, and dioxins.

4.4.5.8 Alternative to plastic

The basic approach to curb waste generation is to reduce the excess use of the said item. Biodegradable mulch (films) will be one of the main alternatives to conventional plastic in agriculture. These films will be degraded naturally, requiring less effort for their removal and disposal. These mulch films will work like plastic mulch in terms of crop growth, weed control, moisture conservation, temperature management, etc., but with the added advantage of being more environment friendly.

4.4.6 Problems associated with proper management

The primary challenges faced for agricultural waste management include the reluctant attitude of stakeholders, lack of awareness about the benefits of recycling agricultural waste, inadequate infrastructure for efficient collection and recycling, lack of information system, and limited funding for investment in new technologies. To overcome these obstacles, service providers can educate farmers about the environmental and economic benefits of recycling agricultural waste, collaborate with local government bodies to improve waste management infrastructure, and seek funding from government grants or private investors for technology gradation.

4.5 Waste to wealth

The mantra of turning waste into wealth is converting the material into a functional product. A large amount of plastic waste being used in different construction works is considered an emerging concept for managing plastic wastes and reducing environmental risks (Zhao *et al.*, 2020). Agricultural plastic wastes may also be used to form carbonaceous nanomaterials, fuel production, wastewater treatment, textile products, and other high-value-added products and reused for planting seedlings, carrying water, storage containers, etc. Therefore, preventing those materials from entering the environment simultaneously saves money. However, the reuse and recycling of agricultural plastic waste is very low ($<10\%$), and there is a need to increase substantially (Cassou, Jaffee, and Ru, 2018). The same may be achieved through the following:

- Public awareness
- Provision of litter bins for plastic waste and fertilizer containers
- Collection and disposal of waste according to category
- Processing of disposed waste
- Institutional strengthening and capacity building
- Management information system

- Technological advancement of waste management and implementation
- Enforcement through institutional monitoring

4.6 The prospect of agricultural waste management

The waste management approach is quite different in developing and developed countries. Waste recycling and reuse are the main emphasis in developing countries like India. However, developed countries focus on reducing the production of waste. We have to change the perception that agricultural waste should be considered a resource, not a threat to environment by finding and implementing suitable ways to collect, recycle, reuse, and use for other activities. The success of agricultural waste management rests on ongoing innovation and development. Waste management is becoming more circular and resource-efficient due to the growing adoption of sustainable practices and cutting-edge technologies. Waste management could be sustainable if renewable energy sources are included and if waste sorting and recycling technologies are advanced.

4.7 Conclusions

The amount of agricultural waste, byproducts, and leftovers rose along with the increased agricultural productivity or output from intensive and industrialized agriculture. Excess fertilizer and manures are applied to achieve more yield and are the primary cause of the loss of nutrients from agricultural fields. Plastic materials are not disposed of properly after use and are considered waste. If properly managed and utilized, these wastes can become valuable resources rather than threaten food safety, animal and human health, or the environment and cause significant pollution issues. Therefore, it is essential to have an extensive understanding of their chemical nature and impact on the ecosystem for better handling and treatment.

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Chapter 5

Food processing waste: Understanding the sources, composition, and characteristics

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Chapter Outline

5.1. Introduction 61
5.2. Source of food processing waste 62
5.3. Animal-derived processing waste (ABPs) 63
5.4. Food processing waste characterization 65
5.5. Food processing waste management and reduction 66
5.6. Food processing waste recycling 66
5.7. Valorization of food processing waste 68
5.8. Conclusion 73
References 74

5.1 Introduction

The terms "food loss" and "food waste" refer to the edible sections of plants and animals that are eliminated during manufacturing or processing (Zhu *et al.*, 2023). "Food loss" is defined as all quantities of human-edible crops and livestock commodity that, through direct or indirect means, are disposed of, burned, or otherwise completely leave the post-harvest/slaughter production/supply chain and do not reenter for any other purpose (like animal feed, industrial use, etc.), up to and excluding the retail level. Therefore, all losses incurred during import quantity storage, transportation, and processing are included. At the production, post-harvest, and processing phases of the food chain, losses comprise the commodity as a whole with its non-edible portions decreasing in edible mass.

Food waste is currently a major global issue that is impacted by the world's population expansion and changes in consumption patterns, and it threatens sustainability and food security due to its negative consequences on the social, environmental, and economic sectors (Schuster and Torero, 2016). Food waste is largely produced by the food supply chain, from production to consumption. Food loss and waste could occur at many stages of the food value chain, including distribution, consumption, processing, post-production, and production. According to FAO estimates, 14% of global food production is lost before it reaches shops. In 2019, it was estimated that 17% of available food was wasted by customers (OECD-FAO, 2021). In 2022, 1.05 billion tons of food were wasted across the three sectors covered by the Food Waste Index report, which equates to 132 kg per capita each year. About 60% of this waste comes from households, with food service coming in second at 28% and retail at 12%.

According to recent data from the European Union (EU), 89 million tons of food waste are produced, and this number is expected to rise 40 times in the future. The world's limited natural resources, including land, are under strain due to population expansion and dietary changes brought on by rising prosperity. This is also increasing greenhouse gas emissions (Schuster and Torero, 2016). Burning was a common method for disposing of surplus cereal remnants, including millet trash. The burning of agricultural waste products, including millet crop residues, is the leading cause of air pollution,

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influencing both global and regional atmospheric chemistry and having a severe influence on climate change, the environment, and human health (Tagade and Sawarkar, 2023).

Fruit and vegetable waste is rapidly biodegradable, which makes it challenging to manage properly, especially in municipal landfills and open burning methods (Lam *et al.*, 2018). Meat and dairy supply only 18% of calories and 37% of protein, but both consume the vast majority (83%) of acreage and water (one-third of 92% agriculture freshwater), and they contribute 60% of agriculture's greenhouse gas emissions. To develop effective food waste intervention measures, it is crucial to understand the underlying causes and associated economic, environmental, and social consequences. This goal necessitates an integrated value chain approach that entails collaboration among a diverse range of stakeholders, including multidisciplinary scholars, policy-makers, the commercial sector, and civil society. An estimated 132 billion euros is the market value of the approximately 58 million tons of food waste (or 131 kg per person) produced each year in the EU. Every year, one-third of the world's food production, or nearly 1.3 billion tons, is lost or wasted. If food waste were a country, it would be the world's third-largest emitter of greenhouse gases, trailing only China and the United States. The resources used to create food that is lost or discarded have a carbon footprint of approximately 3.3 billion tons of CO_2.

5.2 Source of food processing waste

Food waste (FW) is a biodegradable waste that is released from a variety of sources, such as homes, food processing enterprises, and the hospitality sector. It includes both leftover and precooked food. Furthermore, food waste can result from a variety of sources, including overproduction of food, processing, inconsistent logistics, and waste at the home level (Lins *et al.*, 2021). Food processing companies use a variety of methods and techniques to transform raw materials from many different sectors throughout the world, such as fruits and vegetables, dairy, meat, poultry, fish, beer, and grain, into food or other products suitable for human consumption. These processes generate a substantial amount of residue (waste) as byproducts (Sadh *et al.*, 2018).

Food waste can be further divided into categories such as starch-based, meat and fish waste, dairy waste, spent grains, vegetable trimmings, fruit peels, and pulp debris. Multiple studies have revealed that the principal components of food waste are fruits and vegetables (23−65%), animal waste (19−44.23%), and grains (16−32.69%) (Su *et al.*, 2022). Cereals contain nine plant species from the Gramineae family: corn, barley, oats, rice, millet, sorghum, wheat, rye, and triticale, a rye-wheat hybrid (Skendi *et al.*, 2020). The world food supply is dependent on large-scale farming of three cereals: wheat, rice, and maize (Garg *et al.*, 2021). Typically, the processing of cereals and/or plant feedstuffs is limited to the following three steps: cleaning, milling (the main step in the grain-processing industry is either dry or wet milling), or extracting cereal grains and oilseeds; brewing, distilling, or making ethanol; and processing fruits, vegetables, and sugars. The final nutritional value of the byproducts varies substantially depending on the milling method (dry or wet).

Fruits and vegetables are crucial components of the human diet, providing vital nutrients that contribute to human health and well-being, and they are in high demand as the world's population grows and dietary preferences change. Fruits and vegetables account for a significant portion of food waste—more than 42% of total food waste globally. In terms of volume, more than one-third of the world's fruit and vegetable production is wasted before it reaches consumers, resulting in a remarkable 28 million tons of waste. Fruits and vegetables account for the largest portion of loss and waste (31.5% of production), whereas grains and pulses account for the least amount (7.23%) (OECD-FAO, 2021). The processed juice industry contributed 10 to 65% of the organic wastes contained in fruit pulp, while only 2 to 8% of the pulp leftovers ended up in sewage sludge. Approximately 50 to 60% of the processed citrus fruit mass is turned into waste. Furthermore, orange juice manufacturing produces a variety of byproducts, including citrus pulp particles, orange peels, internal tissues, and fibers, all of which are high in sugars, pectins, protein, hemicelluloses, and cellulose. Pineapple waste contains fermentable sugars, readily hydrolyzable cellulose, and hemicellulose. Globally, pineapple wastes make up 50% (w/w) of total pineapple production.

Worldwide, an estimated 114.08 million metric tons of banana waste/loss are produced each year (Acevedo *et al.*, 2021; Sial *et al.*, 2024). This significant wastage is related to their widespread consumption and susceptibility to spoiling. In developing countries, the majority of food waste, 15 to 50% fruit and vegetable loss, happens after harvest due to insufficient infrastructure and processing techniques. In contrast, wealthier countries, such as the United States, have considerably better processing facilities than poor countries. The high process wastes of fruits and vegetables are a consequence of significant processing dependencies on parameters such as geographical location, harvest season, and processing methods (Zhu *et al.*, 2023). The Environmental Protection Agency (EPA) estimated that the food and beverage production and processing industries generated 38 million tons of wasted food in 2016 and increased to 40 million tons in 2019. Nearly 1.3 billion tons of food, including fresh fruits, vegetables, meat, bread, and dairy products, are wasted within

the food supply chain, and this was anticipated to increase from 2.01 billion tons in 2016 to 3.40 billion tons by 2050 (Hoornweg and Bhada-Tata, 2012).

5.3 Animal-derived processing waste (ABPs)

Meat production reached 357.4 million tons in 2021, and by 2030, fish and cattle production is expected to rise by about 14% (OECD-FAO, 2021). Consequently, there will be a notable surge in the generation of animal-derived waste over the course of the next several years. These numbers highlight the urgency of addressing the problem of food waste and looking into long-term solutions (Macavei *et al.*, 2024). One of the major generators of organic waste in the food processing business is the meat production (which includes poultry, bovine, goat, mutton, and swine) and processing industry. Production of livestock was linked to higher rates of environmental degradation than that of vegetable equivalents. Although being the lowest contributor to total food loss and waste (FLW) emissions by mass, the meat group accounted for 34−38% of all FLW production-phase greenhouse gas (GHG) emissions. Animal byproducts (ABPs) are materials derived from animals but not intended for human consumption. However, offal is another form of edible byproduct. ABPs were frequently divided into two categories: edible (tripe stomach), chitterlings with their natural casings (intestines), liver, heart, tongue, kidney, brain, and sweetbreads (lamb or calf testicles), and inedible (hooves, horns, feet, and raw blood and fat). Slaughterhouses are the primary source of animal-derived waste during the production and manufacturing stages. Animal-derived waste in a slaughterhouse includes a variety of elements, including bones (which can make up to 18% of the weight of the live animal) skin, blood, offal, horns, teeth, feathers, combs, hooves, feet, and shells (Macavei *et al.*, 2024).

In 2020, the global production of aquatic animals was estimated at 178 million tons, with more than 157 million tons (89%) used for human consumption. The remaining 20 million tons were used for non-food purposes, mostly to generate fishmeal and oil (16 million tons, or 81%). Fish accounted for 17% of all animal protein and 7% of all protein consumed globally in 2020, and it made up at least 20% of the average daily protein intake for 3.3 billion people. Fish and shellfish waste, depending on the kind of fish and the degree of processing, can make up 20 to 80% of the final product following industrial processing. Crustacean processing creates between 50 and 60% waste. Fish byproducts are divided into two categories: those with a high enzyme content that degrade quickly, such as viscera and blood, and more stable materials, such as bones, heads, and skin.

5.3.1 Bone waste

Slaughterhouses derived bone waste is one of the primary categories of animal-derived waste, with an estimated yearly global production exceeding 130 billion kg (Nassar *et al.*, 2021). The estimated livestock population of 4.89 billion bovines, caprine and ovine animals, pigs, and 27.88 billion poultry animals could explain this large waste volume (Tarafdar *et al.*, 2021). With these data, it is apparent that chicken farming is one of the most important animal industries, producing more than 100,000 tons of meat each year (Ibarz-Blanch *et al.*, 2023).

5.3.1.1 Animal-derived waste from fishing and aquaculture

Marine ecosystems frequently contain waste-derived materials such as jellyfish, bones, shellfish, crustaceans, shrimp, and skin (Zamri *et al.*, 2021). Up to 10 million tons of fish were estimated to be wasted annually in the EU. Marine waste can be extracted using a variety of chemical, biological, and thermochemical methods to yield valuable chemical substances like HAp, calcium carbonate, chitin, collagen, omega-3 fatty acids, and polysaccharides (Macavei *et al.*, 2024; Zamri *et al.*, 2021). Shrimp shells, for instance, have 48% protein, 38% chitin, and 14% mineral (Arya *et al.*, 2022b).

FWs have varied chemical compositions of proteins, carbohydrates, and lipids according to their development and origin. Logically, FW produced from specific agro-based enterprises will be rich in one of the above-mentioned components. This FW composition governs value-added product extraction and other valorization procedures. For instance, different biofuels are created from FW either biologically or thermochemically, depending on their composition (Kavitha *et al.*, 2020). Food waste is often high in moisture (74−90%), volatile solids to total solids ratio (80−97%), and organic matter concentration such as proteins, collagens, polysaccharides, and lipid (Banks *et al.*, 2018). Food waste organic macronutrient composition is 41 to 62% carbohydrates, 15 to 25% protein, and 13 to 30% fat.

The quantity of animal byproducts varies greatly depending on the species, age, sex, live weight, fatness, and collection techniques. The overall byproduct levels often vary from 10 to 30% of the animals' live weight. Actually, the yield of edible byproducts, such as blood and organs, averages 12% in cattle, 14% in sheep, and 14% in hogs. Cattle, pigs, and lambs produce byproducts such as organs, fat, skin, feet, stomach and intestinal contents, bone, and blood, accounting for 66.0, 52.0, and 68.0% of their live weight, respectively. Solid waste generated per head at bovine, lamb, and pig

slaughterhouses accounts for approximately 27.5, 17.5, and 4% of the animal's weight, respectively (Mozhiarasi and Natarajan, 2022). Animal-derived waste is a rich source of organic components such as proteins, collagens, polysaccharides, lipids, and inorganic compounds primarily in the form of calcium phosphate (57.35%) (Braguglia *et al.*, 2018; Macavei *et al.*, 2024).

The results of an earlier study on non-edible food waste, including brinjal waste, potato peels, banana peels, orange peels, eggshells, cow bones, chicken bones, and fish bones, showed that while plant waste samples had higher volatile matter (72.33−80.04%) and lower ash content (1.36−7.79%), animal waste samples showed the opposite pattern. Furthermore, animal waste exhibited less fixed carbon (1.01−2.83%), with the exception of eggshells (22.48%). However, fruit waste has been shown to have a greater fixed carbon content (11.33−24.27%). Additionally, the results showed that the combined samples and animal waste—aside from eggshells—contained higher levels of nitrogen (3.82−5.06%). The total fruit sample had a statistically significant P concentration of 28.21% ± 8.451, with banana peels coming in second with 24.96% ± 11.644. Compared to other waste, vegetable waste had a substantially greater K content (24.90% ± 28.311−37.92% ± 24.833). In eggshell and fish bone waste, the highest concentrations of Ca (68.82% ± 10.778) and Mg (15.37% ± 29.88) were identified, respectively. The waste material under study contains a considerable number of micronutrients, with the exception of zinc and manganese in eggshells (Islam *et al.*, 2023).

Fish composition varies depending on species, sex, age, nutritional state, season, and health. Fish typically comprise 15 to 30% protein, 0 to 25% fat, and 50 to 80% moisture (Khawli *et al.*, 2019). Solid fish waste includes backbones, belly flaps, fish fins, gills, heads, liver, roe, skin, viscera, and meat adhered to the bones (Vázquez *et al.*, 2019). Bones can make up 9 to 15% of the entire fish, while the head, viscera, skin, and scales make up the remaining 9 to 12%, 12 to 18%, and 5%, respectively (Villamil, Váquiro, and Solanilla, 2017). The fish processing industry byproducts can provide useful goods such as proteins, amino acids, collagen, gelatine, oil, and enzymes. These wastes are primarily composed of proteins (58%), fat (19%), crude fiber, and minerals (1%). Furthermore, fish waste contains a lot of monosaturated acids, palmitic acid, and oleic acid (22%) (Kosseva, 2020).

The waste from bananas has a high content of sugars, minerals, cellulose (60−65%), hemicellulose (6−8%), and lignin (5−10%). These materials can be modified through anaerobic degradation and bacterial fermentation to create bioplastics, organic fertilizers, and biofuels like ethanol, biogas, hydrogen, and biodiesel. Furthermore, they can be employed in wastewater treatment techniques by generating inexpensive biofilters and getting activated carbon from banana peels and rachis. Banana pseudostems can also be used to make silver nanoparticles, which are effective in cancer therapy treatments, and nanometric fibers, which are frequently utilized in nanotechnology applications (Acevedo *et al.*, 2021; Sial *et al.*, 2024). About 70% of corn fiber is made up of carbohydrates, which include cellulose, xylan, residual starch, and other elements, including lignin, protein, and phenolic acid (Noureddini and Byun, 2010).

The wheat-milling industry's main byproducts are wheat bran (15−25% of the grain) and germ. Wheat bran contains numerous micronutrients and phytonutrients, including dietary fiber, protein, lipids, alkylresorcinol, ferulic acid, lignans, arabinoxylans, β-glucans, sterols, tocopherols, B-complex vitamins, and minerals (Duţă, Culeţu, and Mohan, 2018). Wheat germ, which accounts for roughly 2 to 3% of the grain, is rich in essential amino acids, unsaturated fatty acids, dietary fibers (soluble and insoluble), minerals, and vitamins B and E. It also contains phytochemicals having antioxidant properties, including flavonoids, phenolics, tocotrienols, tocopherols, carotenoids, and phytosterols (Marti *et al.*, 2014). The grains' dietary fiber, including antioxidants, vitamins, minerals, phytochemicals, and resistant starch, all have various health advantages (Rawat *et al.*, 2023). Millets, categorized as cereals, have a high nutritional value when compared to other major grains such as wheat and rice. Millet waste consists primarily of cobs, husks, stalks, and straw (Tagade and Sawarkar, 2023). They are also a rich source of vitamins and phytochemicals.

Pseudocereals include well-known varieties like buckwheat, amaranth, and quinoa, as well as lesser-known varieties like chia, caihua, pit seed goosefoot, breadnut, celosia, and wattle seeds (Skendi *et al.*, 2020). Maize is principally processed through wet milling, which involves soaking the grain in warm water containing sulfur dioxide, and the processing byproducts include mainly starch as well as lignocellulosic components of corn fiber (Souza *et al.*, 2022). The corn starch byproduct has three forms: waxy starch, ordinary starch, and higher-amylose starch, depending on the amylose percentage of the parent source. The starch produced during wet milling of corn is mostly used to produce sweets and ethanol. The primary uses of starch in the food industry are maltodextrin and glucose syrups, other modified starches, soups, thickeners, infant meals, sweets items, and brewing adjuncts. Starch also serves a range of non-food applications in the textile processing industry, such as packing and as a component in the production of adhesives (Papageorgiou and Skendi, 2018).

Dry milling is primarily employed to process wheat, but it can also be used to polish other grains like rice, oats, and barley. Dry-milling byproducts consist primarily of cereal grains' bran, germ, and endospermic tissue (the aleurone layer).

Bio-functional elements such as phytoestrogens, phenolic compounds, minerals, lignans, vitamins, and fiber are abundant in these grain byproducts (Roasa *et al.*, 2021). These grain byproducts contain a high concentration of lignans, which include phytoestrogens, phenolic compounds, fiber, minerals, vitamins, and bioactive molecules (Papageorgiou and Skendi, 2018). Depending on the raw material selected, the waste composition produced during the processing of fruit and vegetable waste may take characteristics of fruit peel, seed, crop, leaf, straw, stem, root, or tubers (Salim, Singh, and Raghavan, 2017). Dried peels from orange, grape, and lemon have been reported to contain 20 to 30% pectin. Pectin content in apple pomace ranges from 10 to 15% dry weight (Kavitha *et al.*, 2020).

5.4 Food processing waste characterization

Food waste characterization is an important stage in waste management, particularly in terms of valorization, because it can reveal the highest-value products as well as macro- and micronutrients that could be produced from waste under estimation. Furthermore, food waste characterization is a prerequisite to optimizing compost recipes (Bong *et al.*, 2018).

The analysis used to characterize FW varies greatly throughout studies, but it may be broadly classified into two classes. The fundamental physical characteristics such as total solids (TS), volatile solids (VS), TS/VS ratio, pH, and moisture content are included in Group 1. Biochemical characteristics including carbon, nitrogen, carbon/nitrogen ratio (C/N), hydrogen, oxygen, sulfur, particle size, total ammoniacal nitrogen (TAN), NH3, carbohydrates, proteins, lipids, and cellulose are included in Group 2 parameters (Bong *et al.*, 2018). The chemical and physical properties can be evaluated using both modern and conventional (Kjeldahl nitrogen method) approaches.

5.4.1 Elemental composition

CHN(O)S elemental analysis, often known as "LECO analysis," is a low-cost method for estimating the amounts of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) in organic and inorganic materials. This approach can identify even trace elements and is based on the total combustion of solid, liquid, volatile, or viscous materials. This crucial analytical approach provides valuable insights into chemical characteristics, reactivity, and potential applications.

Furthermore, modern non-destructive analytical techniques, such as X-ray fluorescence methodology with small spot analysis, were applied to characterize elemental composition of food wastes such as phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), chlorine (Cl), and nickel (Islam *et al.*, 2023).

5.4.2 Thermal biodegradability

TG is a method where sample weight is determined based on temperature. It offers crucial details about the mass loss, mineralization, and degradation of organic waste at various temperatures (Bhat, Singh, and Vig, 2017).

The degradation process and thermal stability assessment are two of the most recent criteria for characterizing food waste potential for energy production. The TGA technique can be useful in determining the proximate analysis of food waste and in determining the thermal characteristics, such as ignition, burnout temperature, and chemical kinetics of food waste, by using the pyrolysis process. It can also be used to assess the effectiveness of different strategies to optimize energy production from food waste (Elkhalifa *et al.*, 2020; Islam *et al.*, 2023; Slopiecka *et al.*, 2022). For instance, methane yield variations range from 216 to 1476 mL CH_4/gVS due to differences in the organic composition and other parameters such as pH, temperature, and C/N ratio of the samples. These variations are dependent on the region, season, and processing characteristics (Slopiecka *et al.*, 2022). Furthermore, understanding the biodegradable properties of food waste aids in determining the most effective bioconversion technique. Due to the high moisture content of organic raw materials, anaerobic digestion is more suited than thermochemical conversion processes such as combustion and gasification. Furthermore, organic wastes are readily biodegradable substrates. The anaerobic digestion method turns the energy in food waste into a usable fuel (biogas), which can be stored. Furthermore, this process enables the conversion of organic waste into stable soil improvers and valuable items such as fertilizer (Slopiecka *et al.*, 2022).

5.4.3 Functional groups

The functional groups on the surface of the food waste sample and composted products were previously identified using Fourier Transform Infrared (FTIR) spectroscopy (Biyada *et al.*, 2020; Islam *et al.*, 2023). FTIR spectroscopy is an environmentally benign method of analyzing solids, liquids, and gases because it generates a surprisingly low amount of waste. FTIR spectroscopy is a useful tool for distinguishing between organic and inorganic chemicals. It additionally provides important details on the evolution of organic matter and its interactions with heavy metals found in waste

materials. FTIR spectroscopy is used to confirm the degradation of polypeptides, polysaccharides, aliphatic, aromatic, carboxylic, phenolic, and lignin during the vermicomposting of organic wastes (Bhat, Singh, and Vig, 2017).

5.5 Food processing waste management and reduction

The circular economy (CE) model is the efficient use of resources through waste minimization, long-term value retention, primary resource reduction, and closed production cycles, all while adhering to socio-environmental policies (Morseletto, 2020). The conventional economy model is based on linear consumption, which involves extracting raw materials and processing them into completed products and waste. The circular economy seeks to reduce resource depletion by closing energy and material cycles. The CE implementation will boost sales for enterprises and quality for consumers while integrating agents, cities, regions, and governments in a sustainable and long-term model, leading to environmental challenges such as excessive greenhouse gas emissions (Prieto-Sandoval, Jaca, and Ormazabal, 2018).

The general waste management hierarchy has five steps, from the most to the least favored actions, including prevention, reuse, recycling, recovery, and disposal. In 2018−2020, approximately 1.7 billion tons of cereals, protein meals, and processing byproducts (such as cereal bran) were used as animal feed. This figure is expected to climb by 14% over the next decade, reaching 2 billion tons in 2030 (OECD-FAO, 2021). The most popular techniques for valorizing food waste are extraction techniques, composting, and thermochemical conversion, including pyrolysis, gasification, and hydrothermal processes (Macavei *et al.*, 2024). The majority of food processing sector waste (42.6%) was managed by anaerobic digestion; 34.2% was used as animal feed; 12.9% was applied to land; and minor amounts were managed by alternative techniques (Buzby, Fabiano, and Bentley, 2019).

Manufacturing byproducts or wastes contain a range of bioactive components such as polyphenols, flavonoids, caffeine, carotenoids, creatine, and polysaccharides, all of which are helpful to human health; thus, multiple approaches are currently being employed to maximize and identify novel applications (Sadh *et al.*, 2018). Fermentation is one of the oldest waste management technologies that uses microbes to turn industry byproducts or wastes into value-added goods. There are three types of fermentation processes: solid state, submerged, and liquid fermentation, and the ones used depend on the product. Furthermore, several research studies were conducted to identify numerous beneficial chemicals found in food industry byproducts or waste (Sadh *et al.*, 2018).

The natural wastes include a combination of proteins and carbohydrates; under aerobic settings, they can be used to produce proteases, carbohydrase, and other hydrolytic enzymes, whereas under anaerobic conditions, enzymatic action results in the synthesis of biofuels (Bhatia *et al.*, 2021). Mitigating threatening solid waste in the ecosystem appears to be possible through the manufacture of microbial enzymes for catalytic reactions (such as the creation of biofuel, hydrolytic enzymes, flavonoids, pigment, vitamins, etc.) from a variety of natural waste products and raw materials (Arya *et al.*, 2022b). The microbial development (aerobic and anaerobic) and biosynthesis of several microbial metabolites, including biofuel and enzymes, are influenced by a variety of factors, including the producer microorganism, the chemical makeup of the substrate, and physiological characteristics including the size of the inoculum, the source of C and N, and the moisture level of the medium (Arya *et al.*, 2022a,b). It is interesting to support a microbial strategy for multiple enzyme synthesis from these agro-food wastes and then use these enzymes for synthesis in the food, biofuel, and related industries. In addition, procedures including increasing yields, creating effective fermentor designs, controlling production costs and related expenses, optimizing processes, and managing waste are considered in order to provide a realistic picture (Arya *et al.*, 2022a,b).

The industry's recovered animal solid wastes can either be composted or transported to be rendered, which will result in the production of value-added goods including tallow, meat meal, and bone meal (McCabe *et al.*, 2020). Animal byproducts include carcasses, carcass pieces, heads, feet, offal, fat, extra meat, hides, skins, feathers, and bones. Rendering is the process of converting animal byproducts generated during meat production (e.g., slaughterhouses, meat processing plants, butcher's shops, supermarkets, and livestock rearing facilities) into safe edible products for human consumption (fat, mechanically deboned meat, gelatin), animal feed, and industrial and pharmaceutical sectors (such as glue, leather, wool).

5.6 Food processing waste recycling

Large amounts of biological waste are generated and either neglected or dumped in landfills, where they release noxious odors, spread infectious diseases, and contaminate the ecosystem, decreasing the fertility of the surrounding area. Appropriate waste management techniques are necessary, which come at an added expense, to lessen the issues related to

various kinds of waste. These waste products could positively impact the nation's economy and provide additional money if they can be handled and recycled effectively (Kumar Yadav, Hiren Shukla, and Prashanth, 2023).

Fish byproducts must be collected and processed as soon as possible in order to maintain their quality and usage as raw materials in the creation of high-value items. Numerous readily absorbed bioactive peptides found in fish protein can be employed for a range of metabolic processes. A number of their qualities, such as their ability to hold water, absorb oil, gel, foam, and emulsify, make them useful components for a variety of food products. Fishing byproducts contain a significant amount of high-value bioactive micro- and macromolecules that must be exploited with strategic planning and appropriate management. These include lipids, proteins, peptides, amino acids, vitamins, carotenoids, enzymes, collagen, gelatin, chitin, chitosan, and fucoidan (Roy *et al.*, 2023). Biological properties of bioactive chemicals produced from marine sources include antibacterial, antidiabetic, antioxidant, and anticancer properties. The distinct functional and distinctive structures of these high-value compounds make them useful in a variety of industrial sectors, including the food and cosmetic industries (Roy *et al.*, 2023). The majority of conventional waste management techniques currently in use include thermal treatment, anaerobic digestion, composting, landfilling, and the creation of animal feed (Esparza *et al.*, 2020; Jõgi and Bhat, 2020).

5.6.1 Bioenergy production

Recyclable energy produced from agro-residues is thought to be a sustainable closed-loop solution to problems related to energy recovery and waste management (Tagade and Sawarkar, 2023). Pyrolysis is one of the various methods for turning agricultural biomass into bioenergy; it is a potentially less expensive method that yields high-density biofuel. In basic terms, pyrolysis is a thermochemical conversion process that yields pyro-gas (a gaseous byproduct), bio-oil (a liquid), and biochar (a solid byproduct) by thermally breaking down organic biomass to inorganic states in an inert atmosphere (Foong *et al.*, 2022). The variation in the composition and yield of yielded products is determined by the diversity of the biomass composition, which is mostly composed of cellulose, hemicellulose, and lignin in plant waste, and process condition (Tagade and Sawarkar, 2023). Additionally, the key variables influencing the pyrolysis process and determining the composition and distribution of the generated products include temperature, heating rate, nitrogen flow rate, particle size, reactor type, relative gas−solid flow direction, and residence duration (Macavei *et al.*, 2024). Slow pyrolysis generates predominantly solid biochar, whereas rapid and flash pyrolysis yields pyro-gas and bio-oil as principal products. One important byproduct of slow pyrolysis in particular is biochar, which is a cheap, valuable, and sustainable resource for the growing production of lignocellulosic bioenergy. Using a traditional method, 2000 kg of biomass are pyrolyzed to create about 700 kg of biochar. Biochar has many benefits, such as high pH and CCE, high carbon content, porous properties, and high K content. Good biochar qualities enable its use as an adsorbent, a fertilizer, and in other applications (such as catalysts and improved carbon compounds) (Macavei *et al.*, 2024). These benefits allow for a wider range of multifaceted applications, such as diminishing soil acidity, acting as a premium carbon sequestering agent, improving soil aeration and water movement, retaining nutrients and acting as a home for microorganisms to thrive, and complementing K fertilizers (LEAD, 2015; Tagade and Sawarkar, 2023).

In an oxygen-deficient environment, gasification may transform organic materials at 350 to 1000°C in a variety of gasifying mediums (oxygen, steam, air, CO_2, etc.) into flammable synthetic gas. Fuel cells, boiler combustion, and the synthesis of chemical compounds can all employ syngas, which mostly consists of H_2, CO, CO_2, and CH_4 (Macavei *et al.*, 2024). Anaerobic digestion is a low-cost, renewable energy source that generates little residual waste, making it a viable option for managing food waste. Anaerobic digestion consists of three phases: enzymatic hydrolysis, acid generation, and methane gas production (Paritosh *et al.*, 2017). Anaerobic digestion can be divided into two categories: solid-state anaerobic digestion for treating solid organic material such as crop residues, yard trimmings, and the organic fraction of municipal solid waste and food waste, and liquid-state anaerobic digestion for treating liquid organic waste such as sewage sludge, animal manure, and wastewater from food processing units (Paritosh *et al.*, 2017).

5.6.2 Vermicomposting

Vermicomposting is a biological process that turns complex organic wastes into a stable, nutrient-rich fertilizer called vermicompost. Vermicompost is peat-like material rich in plant growth hormones and nutrients in plant-friendly forms. Earthworms and bacteria in their stomachs digest organic waste during the vermicomposting process, resulting in a stable and mature product. Organic waste recycling for use as a soil conditioner is a prominent waste management strategy. Vermicomposting produces organic manures, which can be used to maintain soil fertility and reduce soil pollution.

5.7 Valorization of food processing waste

The population of the earth is predicted to reach 9.7 billion by 2050. Food production must rise and losses along the agri-food chain must decline in order to achieve food security. Nonrenewable resources must be replaced with green materials and technology in order to mitigate the consequences of climate change and global warming (Gari *et al.*, 2024). Effective valorization of waste products in various applications is a vital source in decreasing environmental challenges while tackling obstacles in a sustainable manner.

Food industry wastes represent a significant loss of biomass and nutrients that could be utilized to create functional foods or as a source for other bioproducts like enzymes, antibiotics, biofuels, or biopolymers (bioplastic production) (Esparza *et al.*, 2020; Jõgi and Bhat, 2020). Among the value-added products generated from wasted cereal grains are polysaccharides, organic acids, arabinoxylans, and industrially useful enzymes (Gari *et al.*, 2024). Wheat germ and bran, byproducts of the wheat-milling process, contain a special combination of bioactive ingredients that have been identified as excellent sources of trace minerals, proteins, dietary fiber, phytonutrients, and other micronutrients (Rawat *et al.*, 2023). A significant percentage of the waste and food loss material contains elements that might be used as nutrients and substrates in a range of microbial and enzyme activities to produce useful products. The initial stage of valorization is to ascertain the components of the biowaste (Kosseva, 2020).

5.7.1 Animal-derived waste valorization

The meat industry produces a lot of waste; 46 to 50% of each cow is wasted (Mozhiarasi and Natarajan, 2022). Animal-derived waste is mostly composed of organic compounds including proteins, lipids, and polysaccharides as well as mineral components like calcium phosphate, mostly hydroxyapatite. The valuable composition of animal-derived waste renders it a crucial source for the extraction of chemicals, such as hyaluronic acid (HA), keratin, collagen, and hydroxyapatite (HAp), which accounts for up to 70% of animal bones, that can be utilized to create industrial, pharmaceutical, or medicinal byproducts (Macavei *et al.*, 2024). Slaughterhouse byproducts, such as hides, account for 4 to 11% of live cattle weight and are used in the tanning industry. In 2015, 8.55% of the 5,924,823,536 kg of processed raw hides globally had been turned into leather. In the leather industry, raw hide trimmings make up at least 5% of the entire amount of raw material processed. Taking into account a minimum 20% collagen content (%) based on wet salted raw material, there could be an annual potential of 65,000 tons of collagen available (Flores Tapia, and Brito Moina, 2023). Animal waste has valuable uses as animal feed, fertilizer, industrial byproducts (like fats and oils), and catalysts due to high concentrations of inorganic compounds, primarily calcium phosphate, and organic components, including proteins, collagens, polysaccharides, and lipids (Macavei *et al.*, 2024).

5.7.1.1 Rendering

Edible tallow and lard are rendered fats from cattle and hog leftovers, respectively. They have melting points around 40°C and are used in the production of numerous human meals, including edible fats, jellies, and baking. Inedible tallow or grease is rendered fat from dead farm animals and is used in animal feed, pet food, pharmaceuticals, cosmetics, and industrial products. The process of rendering involves using heat and occasionally pressure to separate the proteinaceous and fat components. Harvested fats are used to make lard and other goods. Protein is extracted and used as a supplement in animal feed (McCabe *et al.*, 2020). The rendering process includes receiving and storing raw materials, reducing size, heating under pressure to eradicate microorganisms and remove moisture, and separating liquid fat and solid protein by pressing or centrifugation. Following that, the solid result can be ground into a powder to produce animal protein meals such as feather meal or meat and bone meal. Before they are shipped, the final goods are stored. Waste particles, liquids, and gases from the rendering process are then treated and disposed of, which often requires some intermediate storage (McCabe *et al.*, 2020).

Rendering techniques can be either dry or wet, and they may be employed in a batch or continuous manner. Three types of fat melting have been reported: batch fat melting, which is applied dry or wet, and continuous methods, which are employed solely in wet circumstances. During the wet rendering process, the liquid, which contains tallow and free water, is separated from the wet particles by pressing or centrifugal force rather than evaporation. In dry rendering, solids and tallow come into contact until the entire material is evaporated and dry. Dry rendering can be done either in batches or continuously. Wet batch condition: Using autoclaves or pressure batch cookers, pre-cut raw material is injected with live steam (140°C) and heated to 100°C under pressure for three to four hours. Although the wet batch conditioning method advantageously can produce high-quality tallow, there are a few drawbacks: (1) time and effort are required; (2) the dry rendered meal absorbs up to 25% of the fat; and (3) viscera must be diced and cleaned.

Dry batch rendering employs indirect heating (steam is confined in a jacket that surrounds the tank containing the material to be rendered) over a 1.5- to 2-hour period at atmospheric pressure to evaporate water from the fat in the cooker. Lastly, the dry solids and tallow are separated when the solids have a moisture content of roughly 10%. Batch dry rendering produces darker tallow than wet rendering. The continuous wet rendering technology is referred to as low temperature or mechanical rendering. In continuous wet rendering systems, raw materials are heated with or without the use of steam to temperatures between 60°C and 100°C in their own juices. This ruptures fat cells and coagulates proteins to generate a heated slurry. Continuous processing combines mechanical and thermal treatments in order to minimize the processing time. The raw material is first passed through a mincer. It is then conveyed to an airtight section, where it is heated in two stages to about 60°C and 90°C, respectively, in a matter of a few minutes.

The most important conditions for creating high quality and accurately estimating rendered fat are low levels of free fatty acids (FFA); low water content; good preservation capabilities; low peroxide value; neutral taste, flavor, and color; and a high solidification point. Byproducts are microbially perishable, comparable to muscle tissue, and even worse in the case of glands and edible offal, which have a higher glycogen content. Therefore, edible byproducts should be produced under refrigeration, chilled quickly after slaughter, handled hygienically, and rendered promptly. Prolonged processing and storage times should be kept to a minimum. Unfresh raw materials should be avoided since they can contaminate wastewater and produce unpleasant smells.

5.7.1.2 Gelatin biopolymers production

One of the most popular biopolymers with a lot of advantageous qualities is gelatin. It is affordable, non-immunogenic, plentiful, water-soluble, biodegradable, nontoxic, and has strong cell adhesion. These traits are frequently customized and used in the pharmaceutical, biological, and food sectors (Goudie *et al.*, 2023).

Gelatin, a very essential protein component, can be created by partially hydrolyzing and denaturing collagen that has low nutritional value. Collagen can be extracted from animal hides, skeleton muscle, offal meals, bone extracts, and skins. "Type A" gelatin is made from young collagen and can be used in a variety of food applications. Examples of this type of gelatin include the skin of pigs, chickens, and some fish. In most cases, a little acid treatment is enough to separate the gelatin from the collagen matrix. On the other hand, "Type B" gelatin—a gelatin derived from mature (highly cross-linked) collagen sources, such as cow skins, bones, and cartilage—is more useful in non-food applications than in food (Xiong, 2018). Whereas Type B gelatin has an isoelectric point close to pH 5.0 and thus carries a net negative or positive charge depending on the acidity of the food, Type A gelatin has a high isoelectric point (pH 6–9) and hence carries a net positive charge in most food uses. In terms of composition, skin is a mixture of kinds I and III collagen, whereas bone and cartilage are primarily composed of types I and III collagen.

5.7.1.3 Keratin biopolymers production

Keratin is a member of the scleroproteins—a family of fibrous structural proteins. Along with collagen, it is the most significant biopolymer found in mammals and is the most prevalent structural protein found in hair, nails, feathers, horns, and claws. Compared to other fibrous proteins like elastin, collagen, and myofibrillar protein, it has a higher cysteine content (Chilakamarry *et al.*, 2021). Many techniques, including chemical hydrolysis, enzymatic and microbiological treatment, dissolution in ionic liquids, microwave technique, steam explosion technique, and thermal hydrolysis or superheated procedure, can be used to extract keratin. But more and more scientists are turning to enzymatic hydrolysate manufacturing because it is a sustainable technique that gives them more control over the final mixtures' composition. Microbially generated keratinase is used to bio-convert keratin waste. The Savinase enzyme is used to remove keratin from wool and feathers. Keratin is extremely biocompatible and biodegradable, which has led to its widespread implementation. It has demonstrated promising outcomes in a variety of industries, including poultry, textiles, agriculture, cosmetics, and pharmaceuticals (Chilakamarry *et al.*, 2021).

5.7.1.4 Protein hydrolysate and peptides production

Meat waste (skin, bone, hair, blood, milk), fish, eggs, and oilseeds are among the materials that can be used to make high-quality hydrolysates (López-García *et al.*, 2022). Collagen and keratin hydrolysates, which contain oligopeptides and amino acids, are in high demand across the economy. Keratin hydrolysates are in high demand in pharmaceuticals and cosmetology as skincare product components. Bioactive peptides with chelating and antioxidant qualities can be produced by hydrolyzing keratin.

Valorization of fish byproducts can yield essential amino acids, collagen, gelatin, polyunsaturated lipids, and enzymes. Fish waste can be used to produce protein hydrolysates that contain relatively tiny bioactive peptides (2–20 amino acids).

Fish hydrolysates frequently have high nutritional value, good amino acid profiles, and positive biological properties. Moreover, Bioactive peptides could transform into value-added medicinal or functional foods capable of preventing, managing, or treating human diseases (Gao *et al.*, 2021). Fermentation, synthesis, and enzymatic hydrolysis are the most prevalent procedures for extracting hydrolyses from fish waste. Fermentation involves cultivating material in a medium with bacteria that release hydrolytic enzymes to break down specific components, resulting in hydrolysates. Proteases hydrolyze proteins in protein-rich materials, yielding a range of peptides. Commercial proteases are used in the enzymatic hydrolysis method to produce fish protein hydrolysate. Proteases can originate from a variety of sources, including (a) microbiological sources; (b) plant sources like papain, ficin, and bromelain; and (c) animal sources like trypsin, pepsin, and chymotrypsin. Many factors affect the bioactivity of the enzymatic hydrolysate, such as the type of protein, pretreatments, the specificity of the enzyme, and the hydrolysis parameters (temperature, solid-liquid ratio, pH, and time) (Razzaq *et al.*, 2019). Membrane and chromatographic separation and purification techniques are the most commonly employed for fractionating protein hydrolysates into various peptides (Alavi and Ciftci, 2023).

5.7.1.5 Hyaluronic acid (HA)

Hyaluronic acid (HA) is a glycosaminoglycan and a key component of vertebrates' extracellular matrix (ECM). It is abundant in synovial fluid, skin, and the vitreous body, where it performs a variety of biological roles. HA serves as a lubricant, shock absorber, space filler, and structural support for surrounding cells and matrix molecules like collagen and elastin fibers. Furthermore, it controls cell differentiation and migration, as well as angiogenesis and inflammatory responses. HA is found in practically all vertebrate tissues, including the vitreous body of the eye, synovial fluid, pig skin, the pericardial fluid of the rabbit, shark cartilage, and other marine creatures (Elhiss *et al.*, 2024).

5.7.1.6 Biofuel production

Slaughterhouse and poultry wastes are high in protein and could be a good substrate for three types of biofuel production (Mozhiarasi and Natarajan, 2022).

5.7.1.7 Biodiesel production

Poultry and slaughterhouse wastes are potential resources of biodiesel production due to their high lipid content and low cost when compared to vegetable oil. Biodiesel is the mono-alkyl esters (ethyl or methyl) of long-chain fatty acids produced by trans-esterification of triglycerides with alcohols (methanol or ethanol) in the presence of an acid/alkali catalyst (often NaOH/KOH). The oil/tallow produced from renewable energy feedstocks would be trans-esterified to yield biodiesel. The resulting biodiesel could be combined with diesel depending on its qualities (Mozhiarasi and Natarajan, 2022).

5.7.2 Plant-derived waste valorization

5.7.2.1 Biofuel production

Biofuels are utilized in the solid, liquid, and gaseous phases of matter. They are typically found in solid form as pellets, charcoal, wood chips, etc.; in liquid form, biodiesel and bioethanol are particularly noticeable. Biofuel can be found in gaseous form as biogas, which is mostly created by anaerobic fermentation or gasification, which is the partial oxidation of waste at high temperatures.

5.7.2.2 Bio-methane production

Large complex polymers including proteins and carbohydrates that are included in waste matrices (primarily organic wastes such as livestock manure, food wastes, sewage sludge, crop residues agricultural byproducts, fish waste, and the organic fraction of municipal solid wastes) are first hydrolyzed, and then fermented to produce CO_2 and hydrogen acetate, which are then converted to methane. The processes known as hydrolysis, acidogenesis, acetogenesis, and methanogenesis are all caused by distinct classes of bacteria (Guo *et al.*, 2022). There is a distinct functional group (or guild) of microorganisms that perform each of these successive steps and that are dependent on external environmental factors such as temperature, pH, C:N ratio, and redox potential (Lim *et al.*, 2020). The extracellular hydrolases (e.g., cellulase, xylanase, pectinase, amylase, lipase, and protease) secreted by hydrolytic bacteria hydrolyze polymeric substrates, primarily polysaccharides (cellulose, hemicellulose, starch), lipids, and proteins. This process releases monomers or oligomers, such as glucose and cellobiose from cellulose, glucose and maltose from starch, xylose from hemicellulose, amino acids from proteins, and long-chain fatty acids (LCFA) and glycerol from lipids. Although the

hydrolytic bacteria are phylogenetically varied, the majority of the bacteria discovered in AD bioreactors belong to the two phyla Firmicutes and Bacteroides.

5.7.2.3 Bio-alcohol production

Food/agricultural residues are typical lignocellulosic substrates that have acted as a potential source for the manufacturing of ethanol, therefore giving a viable solution in lowering greenhouse gas emissions (Guo *et al.*, 2022). Corn fiber byproduct, which accounts for approximately 10% of the weight of corn kernels, is a promising raw material for making second-generation cellulosic bioethanol (Guo *et al.*, 2022) and value-added products such as dietary fiber, corn fiber oil, corn fiber gum, and xylitol.

The production of second-generation ethanol is currently well understood to be primarily focused on exposing or separating more starch or carbohydrates from lignocellulosic substrates through various methods, such as increasing grinding capacity selectively and enzymatically. The next stage, saccharification, in producing ethanol from lignocellulosic substrates involves converting starch or carbohydrates to reducing sugars like glucose using dilute acid pretreatment and commercial enzymes such as α-amylase, β-amylase, and glucoamylase. Subsequently, lignocellulosic content is further converted to ethanol and CO_2 through fermentation of reducing sugars by yeasts such as *Saccharomyces cerevisiae* (Guo *et al.*, 2022). The yeast cells' invertase and zymase enzymes help convert the reducing sugars to crude ethanol. One of the main obstacles in the fermentation process is the intrinsic release of inhibitor chemicals during the breakdown of lignocellulosic material into sugars (Soares *et al.*, 2023).

5.7.2.4 Bio-hydrogen production

Furthermore, solid food waste from processing and agriculture is a rich supply of substrate for bio-H_2 production. Enzymes such as cellulase promote the initial enzymatic breakdown of the carbohydrate component of cellulosic biomass to fermentable sugars in the anaerobic dark fermentation process used to create H_2 (Kazmi *et al.*, 2024; Nayak and Bhushan, 2019). The next step is to produce organic acids through thermophilic heterotrophic fermentation of carbohydrates (Gu *et al.*, 2024; Su *et al.*, 2022). Photoheterotrophic fermentation transforms organic acids into hydrogen. Because it is clean and renewable, emits no greenhouse gases (GHG), and has a high energy content, hydrogen produced in this manner is a possible replacement for fossil fuels. Ammonia and methanol are two more typical chemicals created utilizing bio-H_2 (Gu *et al.*, 2024; Nayak and Bhushan, 2019).

5.7.3 The value-added components retrieval and extraction

Food waste and byproducts may contain proteins, carbohydrates, lipids, fibers, antioxidants, pigments, vitamins, and flavoring compounds that can be recovered and utilized to manufacture cosmetics, nutraceuticals, food additives, and feed (Nayak and Bhushan, 2019). Value-added components are selectively removed from the food matrix using a combination of biochemical, chemical, or thermal/physical techniques, after which they are modified into higher-value foods or additives. Different pretreatment and extraction procedures may be used in the processes to separate value-added chemicals from the food waste matrix. During the pretreatment stage, enzymes like pectinase, α-amylase, and cellulase are added before the solvent extraction to aid in the breakdown of cell walls and the hydrolysis of structural polysaccharides to improve solvent accessibility and the release of bioactive ingredients such as oils, natural pigments, and antioxidants and also to reduce the extraction time (Sowbhagya and Chitra, 2010). The modern pretreatment technique uses supercritical fluids, including CO_2, as an alternative extracting solvent for bioactive components from the waste matrix more quickly than with traditional organic solvent extraction simply due to its food matrix's significant penetration capability. Pulsed electric field (PEF), microwave-assisted extraction (MAE), and ultrasound-assisted extraction (UAE) are some of the more sophisticated and recently developed pretreatment techniques for bioactive component extraction. Solvent extraction is the traditional technique used to recover bioactive components from food waste matrices. It involves using solvents such as methanol, ethanol, acetone, or their aqueous phase. The third isolation process step is to isolate or clarify the bioactive component from the extract, which may comprise one or more target components or contaminants. Traditional approaches include membrane separation (reverse osmosis, ultrafiltration, nanofiltration, and microfiltration) and resin adsorption (Nayak and Bhushan, 2019).

Cereal, pulse, and oilseed processing byproducts, particularly the brans/hulls, are high in phenolic compounds with antioxidant qualities, although they are often dismissed as low-value animal feed or waste. Byproduct phenolics' potential health-promoting benefits are hampered by the low bio-accessibility and bioavailability of bound phenolic components (Roasa *et al.*, 2021). Phenolic compounds are classified into simple phenolics and highly complicated polyphenols based on their chemical compositions (Tsao, 2010). Lignans, stilbenes, flavonoids, and phenolic acids are

the four primary classes of dietary phenolics; polyphenolic amides and tannins are the minor subcategories (Roasa *et al.*, 2021). Polyphenols can be either soluble or insoluble in aqueous organic solvents. Soluble phenolics occur naturally in free form or in combination with sugars or short peptides, and they are preferentially extracted by standard extraction procedures as extractable polyphenols (EPP). Insoluble phenolics, which include both polymeric polyphenols like pro-anthocyanidins and bound phenolics, are always conjugated with plant cell wall macromolecules like pectin, cellulose, hemicellulose, and structural proteins by covalent bonds, hydrogen bonds, and hydrophobic interactions (Shahidi and Yeo, 2016; Zhang *et al.*, 2020). Alkaline or enzymatic hydrolysis methods, as well as advanced techniques such as microwave, ultrasound-assisted hydrolysis, and accelerated solvent extractions have been used to liberate bound phenolics that could not be isolated and that remained as solid residue after conventional extraction methods (Zhang *et al.*, 2020).

The food industry uses a variety of technologies, including microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), ultrasonic-assisted extraction (UAE), and high hydrostatic pressure technique (HHP), to produce food bioactive compounds and ingredients from fruit and vegetable waste and byproducts. Fruit and vegetable wastes can be biorefined using techniques such as hydrothermal carbonization, pyrolysis and gasification, fermentation, incineration, anaerobic digestion (AD), and incineration to produce biofuels (Zhu *et al.*, 2023).

Many studies have been conducted on the extraction of pectin from fruit-processing industrial waste, the recovery of phenolics and organic acids from mango kernels, and the extraction of pigments like carotenoids, polyphenolic compounds, vitamins, dietary fibers, and enzymes from mango peels. Other studies have focused on the extraction of biocompounds like bromelain from pineapple stems, the extraction of protein powder from coconut-processing industrial waste, and other processes. Similarly, pectin, a food ingredient used mostly in the culinary, chemical, and pharmaceutical industries, is mainly derived from FW, which comprises sugar beet pulp waste, orange peel, and apple pomace.

5.7.3.1 Create bio-adsorbents to treat wastewater

Traditional adsorbents, such as activated carbon, have been used for a long time in the wastewater treatment sector. Nevertheless, the manufacture of adsorbents is linked to significant environmental impact and expensive raw resource consumption, which has hindered their broad application. In addition to helping to address local environmental problems, the possibility of recycling wastes from the food processing industries as inexpensive adsorbents for toxicant removal from water would also support local material reuse and recycling, thus fostering sustainable development.

The production of high-quality activated carbons and their subsequent application as an adsorbent for wastewater treatment have been made possible by the utilization of lignocellulosic-rich agricultural waste byproducts and residues, which are less expensive and environmental. The benefits of using lignocellulosic waste byproducts/residues include their low cost and wide availability, as well as their high lignin and cellulose contents. These byproducts are rich in various functional groups, including ethers, carboxylic, aldehydes, ketones, and alcohols (Karić *et al.*, 2022; Nayak and Bhushan, 2019). These groups can bind to many water-based contaminants by forming complexes with ionic species in solution and donating an electron pair through the functional group on the adsorbent (Karić *et al.*, 2022; Nayak and Bhushan, 2019). Lignocellulosic-rich agro-waste byproducts/residues can be converted into bio-adsorbents using two ways. The physical synthesis process comprises heating biomass at lower temperatures to form chars (carbonization), followed by heating at higher temperatures in the presence of an oxidizing agent such as steam or CO_2 (activation). The chemical process involves impregnating the biomass with an activating agent, which is then carbonized (heated in an electrical furnace under inert atmospheres at lower temperatures). The activating agents can be classified as basic solutions (sodium hydroxide, calcium hydroxide, sodium carbonate) and mineral-based and organic-based acids. The activating agents are classified as basic solutions (sodium hydroxide, calcium hydroxide, sodium carbonate), mineral-based and organic-based acid solutions (hydrochloric acid, nitric acid, sulfuric acid, tartaric acid, citric acid, thioglycolic acid), organic compounds (ethylenediamine, formaldehyde, epichlorohydrin, methanol), and oxidizing agents (hydrogen peroxide).

5.7.4 Biomaterials production

5.7.4.1 Bioplastic production

European Bioplastics defines "bioplastic" as a plastic substance that is biodegradable, bio-based (made from a renewable source), or combines both features. Bioplastic production techniques fall into five categories based on raw material source and polymer synthesis technology: (1) extracted directly from biomass; (2) made from natural or genetically altered organisms; (3) made from bio-based monomers; (4) synthesized from petrochemicals; and (5) created by combining these approaches and formed polymers (Jõgi and Bhat, 2020).

5.7.4.1.1 Direct biopolymers extraction Natural biopolymers such as starch, cellulose, potato protein concentrate, and gluten are recovered directly from biomass and partially modified into thermoplastic polymers using compression and injection molding methods (Arya *et al.*, 2022b).

5.7.4.1.2 Bioplastic production by natural or genetically modified organisms Alternative methods for producing biopolymers require pretreatment technologies, which can be classified as chemical, physical, or biological. Reducing the size of the substrates by enzymatic hydrolysis, eliminating inappropriate inert components, and releasing lipid, polysaccharide, and protein monomers from the waste matrix are the main goals of the pretreatment process. These extracted monomers are then combined with fermentation, chemical processing, and polymerization to create bio-polymers, such as polylactic acid (PLA), polybutylene succinate (PBS), and polyethylene (PE) (Jõgi and Bhat, 2020; Nayak and Bhushan, 2019).

5.7.4.2 Enzymes recovery

Using agri-food wastes and byproducts for the manufacture of bioplastic would reduce manufacturing costs along with waste and byproduct production (Jõgi and Bhat, 2020; Nayak and Bhushan, 2019). The huge commercial applications of enzymes, as well as the ideal composition (high carbohydrate and nutritional content) and lower cost of food and agro-industrial waste, inspired researchers to create biorefinery systems for enzyme recovery from food waste. In brief, these wastes are among the best substrates for the growth of bacteria, which leads to their disintegration and the concurrent synthesis of enzymes. Enzymes like amylases, pectinases, and cellulases are used in the food and biofuel industries, while tannery wastewater is treated with tannase to reduce tannic acid levels. Wastes including wheat bran, corn gluten meal, banana solid wastes, and spent grain are commonly used as fermentation mediums for alpha amylase recovery. Solid-state fermentation of grains has been shown to produce hydrolytic enzymes like xylanase, pectinase, and cellulase. Many hydrolytic enzymes from the solid-state fermentation of grape pomace have been described, including xylanase, pectinase, and cellulase. Waste from citrus peels is rich in cellulose, hemicellulose, and pectin; these ingredients have been used to make a variety of pectinolytic enzymes. The fermentation of sugarcane bagasse has produced a number of industrially significant enzymes, including cellulase, xylanase, amylase, and lipase. However, cost estimates are not affordable because there is no operating biorefinery for food wastes to recover enzymes on an industrial scale (Nayak and Bhushan, 2019).

5.7.4.2.3 Organic acids recovery Microbial fermentation, which has three widely utilized processing categories, submerged fermentation, surface fermentation, and solid-state fermentation, is the technology used to manufacture organic acid, an important citric acid. Citric acid is widely used in a variety of industries, including pharmaceuticals, food, chemicals, and cosmetics. Citric acid is produced by a variety of microorganisms, the most common of which are filamentous fungi such as *Aspergillus niger* and the yeast *Yarrowia lipolytica* (Książek, 2024).

The main agro-industrial substrates used to produce citric acid are molasses and/or starch, sucrose-based media. However, other residues have also been studied for their potential use as citric acid substrates, including coffee husk, beet molasses, apple pomace, grape pomace, kiwi fruit peel, pineapple waste, cassava bagasse, and other cellulosic substrates (Książek, 2024; Nayak and Bhushan, 2019; Yafetto, 2022).

5.7.4.2.4 Bio-fertilizers production (composting technology) Under controlled circumstances, aerobic digestion (composting) or biochemical fermentation of biodegradable organic food or agro-industrial waste by microorganisms can produce stable pathogen-free biofertilizers and soil conditioners. Bacteria start the composting process, whereas fungi dominate the entire process (Hernández-Lara *et al.*, 2022; Zainudin *et al.*, 2022). The effectiveness of composting technology is affected by temperature, aeration, moisture content, pH, C/N ratio, particle size, and degree of compaction. Compost maturity is affected by the C/N ratio, even though aeration has been found to be the most important factor affecting compost quality. The size of the particles in food waste greatly affects porosity, which ultimately affects gas/water exchange, aeration, and water-holding capacity (Nayak and Bhushan, 2019; Noor *et al.*, 2024).

5.8 Conclusion

Food processing waste, an inevitable byproduct of the global food industry, presents challenges and opportunities. By understanding its sources, composition, and characteristics, we can better manage and utilize these materials, turning waste into valuable resources. This chapter has highlighted the diverse origins of food processing waste, ranging from agricultural residues to byproducts of manufacturing processes. The composition of these wastes varies significantly, influenced by the

type of food processed and the specific practices employed. Key characteristics such as moisture content, nutrient composition, and the presence of bioactive compounds are critical in determining their potential for reuse and environmental impact. Effective management of food processing waste requires a comprehensive approach that considers the entire life cycle of the waste material. Innovative technologies and sustainable practices can transform waste into products such as biofuels, animal feed, and organic fertilizers, reducing environmental pollution and promoting a circular economy.

Moreover, understanding the characteristics of food processing waste can aid in developing tailored waste treatment and recycling strategies that maximize resource recovery and minimize adverse environmental effects. In conclusion, a thorough grasp of food processing waste's sources, composition, and characteristics is essential for advancing sustainable waste management practices. By leveraging this knowledge, we can move toward a more resilient and environmentally friendly food system, where waste is not merely discarded but is recognized as a valuable resource for future use.

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Chapter 6

Water footprints of the global agriculture sector

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Chapter Outline

6.1. Introduction 79
6.2. The global value of water in agriculture 80
6.3. Ecological footprints and agriculture 81
6.4. Water scarcity in agriculture: Causes, impacts, and mitigation 82
6.5. Understanding water footprints: Definitions and components 83
6.6. Water footprint of global food production 84
6.7. Water footprint for specific agricultural productions with energy purposes 85
6.8. Assessing water footprints: Methodologies and tools 86
6.9. Factors affecting water footprint 90
6.10. Decreasing water footprints through precision agriculture 92
6.11. Conclusion 93
References 94

6.1 Introduction

Water is essential for the sustainability of life. It underpins the global agricultural sector. Water plays a pivotal role during every biological process, from photosynthesis in plants to hydration in animals. Adequate and suitable water is required for the ultimate agricultural production. Unsuitable water quality leads to reduced crop yield, low-quality production, and compromised food security. The global agricultural sector is the largest water-consuming sector. Approximately 70% of freshwater on Earth is extracted only for agricultural use. Effective and sustainable management strategies are required to meet this enormous demand for water in order to maintain environmental sustainability and long-term agricultural productivity.

The demand for food is rising at a rate never seen before as the world's population continues to expand. Concurrently, climate change, urbanization, and industrialization are exacerbating water scarcity issues, further complicating the challenge of meeting agricultural water needs. The intricate relationship between water and agriculture extends beyond mere usage; it encompasses the economic, ecological, and social dimensions that influence global food systems. Understanding and managing water footprints in agriculture is, therefore, critical to ensuring a resilient and sustainable future for food production.

This chapter aims to provide a comprehensive exploration of the water footprints within the global agriculture sector. By examining the various dimensions of water use and management in agriculture, we seek to illuminate the multifaceted nature of this critical resource. The chapter is structured with the global value of water in agriculture; ecological footprints and agriculture; water scarcity in agriculture: causes, impacts, and mitigation; understanding water footprints: definitions and components; water footprint of global food production; water footprint for specific agricultural productions with

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energy purposes; assessing water footprints: methodologies and tools; factors affecting water footprint; decreasing water footprints through precision agriculture; recommendations for adaptation techniques to meet water demand; and water footprint in future trend scenarios. This chapter reveals the importance of sustainable water management in global agriculture and outlines future directions for research and policy interventions.

6.2 The global value of water in agriculture

6.2.1 Exploring the intrinsic value of water in agricultural production

Water is the cornerstone of agricultural production, playing an indispensable role in both plant and animal agriculture. In crop production, water is essential for photosynthesis, the process by which plants turn sunlight into energy. It facilitates the absorption of essential nutrients from the soil, supports the development of plant tissues, and regulates temperature through transpiration. Without adequate water, crops suffer from reduced growth rates, lower yields, and diminished nutritional quality.

For livestock, water is equally vital. It is necessary for digestion, nutrient absorption, waste excretion, and thermoregulation. Hydration affects the health and productivity of animals, influencing milk production in dairy cows, growth rates in meat animals, and egg production in poultry. Beyond direct consumption, water is also essential for producing the feed that livestock depend on, linking the water needs of plant and animal agriculture.

The intrinsic value of water extends to its role in maintaining soil health. Proper irrigation practices help preserve soil structure, prevent erosion, and promote the activity of beneficial microorganisms. These factors collectively enhance soil fertility and contribute to sustainable agricultural practices. In essence, water is not just a physical input but a critical driver of farming ecosystems' overall health and productivity.

6.2.2 Economic implications and global significance

The economic implications of water use in agriculture are vast. Agriculture is a major consumer of water, accounting for approximately 70% of global freshwater withdrawals. The availability and efficient use of water directly impact agricultural productivity and profitability. Regions with abundant water resources often enjoy higher agricultural yields and lower production costs, while water-scarce areas face increased challenges and expenses.

The economic significance of water in agriculture is particularly evident in developing countries, where agriculture constitutes a significant portion of the GDP and employs a large percentage of the population. Water scarcity in these regions can lead to reduced crop and livestock productivity, higher food prices, and increased vulnerability of rural communities. Conversely, efficient water management practices can enhance agricultural productivity, boost rural incomes, and contribute to economic stability.

On a global scale, the interplay between water use in agriculture and broader environmental and socioeconomic factors is increasingly apparent. Climate change is altering precipitation patterns and exacerbating water scarcity in many regions while growing populations and urbanization intensify the demand for water. Effective water management in agriculture is therefore critical not only for food security but also for achieving sustainable development goals and maintaining economic stability worldwide.

6.2.3 Case studies highlighting water's role in different agricultural contexts

6.2.3.1 Drip irrigation in Israel

Israel is renowned for its innovative approach to water management in agriculture. Faced with arid conditions and limited freshwater resources, Israeli farmers have adopted advanced irrigation technologies, such as drip irrigation. This system delivers water directly to the plant roots, significantly reducing water loss due to evaporation and runoff. As a result, Israel has achieved high levels of agricultural productivity and efficiency, even in a challenging environment. The success of drip irrigation in Israel demonstrates the potential of technology-driven water management solutions to enhance agricultural sustainability.

6.2.3.2 Rice cultivation in the Mekong Delta

The Mekong Delta in Vietnam is one of the world's most productive rice-growing regions, benefiting from abundant water resources provided by the Mekong River. Traditional irrigation practices have long supported high rice yields. However, recent changes, including upstream dam construction and climate change, have altered water availability, threatening this productivity. Farmers in the Mekong Delta are adapting by implementing water-saving techniques such as

alternate wetting and drying, which conserves water while maintaining high yields. This case highlights the necessity of adaptive water management in response to changing environmental conditions.

6.2.3.3 Drought-resilient farming in sub-Saharan Africa

In sub-Saharan Africa, recurrent droughts pose significant challenges to agriculture. Farmers in this region are increasingly adopting drought-resilient practices to mitigate these impacts. Techniques such as planting drought-tolerant crop varieties, using rainwater harvesting systems, and practicing conservation agriculture help conserve water and maintain productivity during dry periods. These strategies not only enhance resilience to climate variability but also contribute to food security and livelihoods in vulnerable communities. The experiences of farmers in sub-Saharan Africa illustrate the critical importance of resilient and sustainable water management practices.

There are a lot of studies that underscore the diverse ways in which water management practices influence agricultural outcomes across different contexts. These studies highlight the global value of water in agriculture and the potential for innovation and adaptation to address water-related challenges, ensuring sustainable and productive agricultural systems worldwide.

6.3 Ecological footprints and agriculture

6.3.1 Ecological footprints and their relevance to agriculture

The ecological footprint (EF) serves as a resource assessment tool that quantifies the environmental impacts linked with human activities or communities. It measures the resources consumed by a specified human population and the environment's ability to supply, manage, or generate waste sustainably (Genta *et al.*, 2022). This evaluation encompasses various aspects such as food production, energy consumption, housing, transportation, and waste disposal and can change each year with population growth, consumption, and productivity. In agriculture, EF is highly relevant because agriculture is one of the most significant human activities affecting the environment. During the production of an agricultural product, a specific amount of environmental resources is used based on climatic conditions, field management, and type of product (Soltani *et al.*, 2021). However, the number of resources used in production is not visible in the final product.

For this reason, EFs in agriculture are used to evaluate the contribution of farming activities to global sustainability, mitigate the adverse effects of agriculture on the environment, and ensure long-term food security. Not only this, but they also help assess various factors such as greenhouse gas emissions, water consumption, and loss of reactive nitrogen. Studies have shown that the use of chemical fertilizers in agriculture can notably increase greenhouse gas emissions (NO_2) and enhance climate change issues, resulting in overall ecological imbalance (Ozlu and Kumar, 2018).

6.3.2 Ecological impacts of agricultural practices

Agricultural practices exert a negative impact on the physical environment, leading to issues such as soil erosion, loss of vegetation cover, and water and air pollution. Despite these significant effects, agriculture plays a crucial role in recycling and conserving natural resources, reshaping the environment, and establishing new wildlife habitats (Waithaka, 2023). Notably, agriculture also contributes to reducing 21 to 37% of global emissions responsible for climate change, such as carbon dioxide, methane, and nitrous oxide (Lynch *et al.*, 2021). Also, it accounts for 70% of global freshwater withdrawals and has witnessed a 500% increase in global fertilizer usage over the past five decades (Turcotte *et al.*, 2017). Unsurprisingly, agriculture has inflicted severe impacts on biodiversity and ecosystem services. Human activities, such as the conversion or degradation of natural habitats, which are predominantly driven by changes in land use resulting from intensified agricultural practices such as enlarging field size, shortening crop rotations, and increasing fertilizer and pesticide usage, are causing the depletion of crop genetic diversity and elevate vulnerability to both biotic and abiotic stresses.

Moreover, this trend has been linked to a significant decline in vertebrate, invertebrate, and plant species richness while reducing the resilience of crops to pests, diseases, and environmental changes (Newbold *et al.*, 2015). Floods and irrigation systems can bring changes in the quantity and composition of decomposable nutrients. They can alter nitrogen fluxes that can impact the growth of plants, soil microbial biomass, and biodiversity (Barros-Rodríguez *et al.*, 2021). Methods such as fires, tilling, and ploughing have been shown to significantly affect bacterial communities, leading to a reduction in their biodiversity (Verzeaux *et al.*, 2016). European agricultural practices, characterized by high farm management intensity, monoculture landscapes, mechanized production systems, substantial nutrient input, high biomass production, and intensive pesticide treatments, play a pivotal role in the degradation of freshwater quality (Schürings *et al.*, 2024).

6.3.3 Strategies for mitigating negative ecological footprints

Various sustainable agricultural practices, such as agroforestry, organic farming, crop rotation, and precision agriculture, can be incorporated that aim to minimize environmental degradation while maximizing productivity (Muhie, 2022). Furthermore, promoting sustainable consumption patterns, reducing transportation and food waste, improving water management, and investing in research and technology for eco-friendly farming methods are essential steps in reducing the EF of agriculture. Organic farming proves to be vital, as it minimizes synthetic fertilizers use, enhances soil health, promotes biodiversity, and produces high-quality food while reducing environmental burdens (Gamage *et al.*, 2023).

Diverse crop rotation or diversifying farms with habitat patches, multiple crops, hedgerows, and grass strips sustains biodiversity, soil quality, nutrient cycling, water retention, pollination, and pest control and potentially increases yields (Reece and Kremen, 2020). Zero or reduced tillage minimizes soil disturbance, maintains soil structure and moisture, and reduces greenhouse gas emissions and energy consumption (Kumari *et al.*, 2023). Additionally, regenerative agriculture restores ecosystem functioning; enhances productivity; improves biodiversity, water cycles, and climate resilience; and promotes soil health (Keesstra *et al.*, 2018). Precision agriculture, emerging as a promising approach, optimizes resource use, reduces environmental impacts, and improves productivity through technologies such as remote sensing, geographic information systems (GIS), and global positioning systems (GPS) (Korneeva *et al.*, 2023).

6.4 Water scarcity in agriculture: Causes, impacts, and mitigation

6.4.1 Identifying the causes and consequences of water scarcity in agriculture

Water scarcity in agriculture arises from various interconnected factors. The increasing demand for water to produce food and feed, support industrial processes, and meet urban and rural needs contributes significantly to surface water scarcity (Ingrao *et al.*, 2023). Each year, over 4 trillion m^3 of freshwater is extracted from water bodies due to factors like population growth, improved living standards, and expanded irrigation. Agriculture alone accounts for nearly 70% of this water withdrawal (Aivazidou *et al.*, 2016). The altering precipitation patterns and increasing temperatures, especially in regions like the eastern Mediterranean, exacerbate water scarcity while challenging agricultural productivity (Molénat *et al.*, 2023). Reduced water availability limits crop growth, lowers crop yields, and impacts rural livelihoods and national economic development. Overextraction of water leads to depleted water tables, soil degradation, and increased water salinity, further reducing agricultural productivity (Sabzevar, Rezaei, and Khaleghi, 2021).

On the other hand, unsustainable irrigation practices with inefficient systems can cause significant water losses (Koech and Langat, 2018). Non-point pollution, characterized by agricultural chemicals, can contaminate water sources, making them unsuitable for irrigation and consumption (Baccour *et al.*, 2021). Both water availability and water quality have been closely associated with human health, as poor water quality resulting from water contamination can lead to waterborne infectious diseases such as dysentery, diarrhea, and jaundice, affecting both human and livestock health. Water scarcity can also exacerbate social unrest and urban migration, increase urbanization pressures, and lead to conflicts over shared water resources, such as those between India and Bangladesh or Syria and Iraq (Musie and Gonfa, 2023). Inadequate regulations, weak enforcement of water laws, and lack of sustainable water management policies can further contribute to the misallocation and overuse of water resources.

6.4.2 Impacts on food security, biodiversity, and livelihoods

Agricultural water supply plays a crucial role in promoting crop production and alleviating hunger, particularly in developing countries, where food production is often increased through the expansion of irrigation areas and water extraction. Reduced water availability can decrease crop yield and increase carbon dioxide levels and temperature stress. It can lead to crop failures, which can exacerbate food insecurity, especially in regions heavily reliant on agriculture for food (Tijjani, Giri, and Woznicki, 2022). Freshwater scarcity affects many ecosystems, causing habitat and biodiversity loss and increasing pollutant concentrations in rivers. This reduces species richness and risks extinction for aquatic organisms (Pierrat *et al.*, 2023). Beyond climate issues, non-climatic factors like age, income, and gender also contribute to vulnerability to water scarcity (Leal Filho *et al.*, 2022). Water scarcity directly impacts farmers' incomes by reducing crop yields, potentially compelling them to migrate away from water-scarce regions as they struggle to sustain their livelihoods amid diminishing water resources and increased poverty. Women, in particular, are negatively affected more than men, as they are often left behind without adequate support to manage the farms single-handedly and tend to families. Chronic shortages of safe drinking water can further increase the risk of waterborne diseases and social conflicts, particularly in regions with shared or scarce water resources.

6.4.3 Approaches for reducing water scarcity risks in agricultural systems

Water scarcity can be alleviated by combining both water quality and quantity solutions, including inter-basin water transfer, constructing dams and reservoirs, unconventional water use, and improving surface water quality, ensuring effective water capturing, storage, and distribution during scarcity (Li *et al.*, 2024). Advanced pressurized irrigation systems with optimized irrigation schedules enhance water productivity and minimize water losses (Nikolaou *et al.*, 2020). Effective agricultural practices such as diversified crop rotation and continuous cereal cropping systems optimize water use efficiency, reduce irrigation demand, and enhance crop productivity. Water-saving techniques for rice cultivation, such as alternate wetting and drying, aerobic rice systems, and systems of rice intensification, significantly reduce water consumption while improving yield (Mallareddy *et al.*, 2023) (Figure 6.1).

Smart greenhouses with AI systems enhance water productivity and mitigate water scarcity by increasing crop yield with lower labor costs. Regenerative agriculture fosters healthier soils that absorb and retain more water and improve productivity without irrigation. Reusing treated wastewater and rainwater harvesting addresses water scarcity in regions with limited resources, improves water quality by removing pollutants, and reduces groundwater reliance. Desalination removes salts from seawater and brackish water, producing potable water suitable for various uses (Moossa *et al.*, 2022). Sustainable management practices, such as water pricing mechanisms, water rights allocation, and water-use quotas, can also help alleviate the issue of water scarcity by promoting effective water use.

6.5 Understanding water footprints: Definitions and components

6.5.1 Defining the concept of water footprint and its significance

The water footprint (WF) is a multidimensional measure of the total freshwater consumption associated with the production of goods and services at various levels, including both direct and indirect water use (Okutan and Akkoyunlu, 2021). In other words, it accounts for the water consumed by each source and polluted volumes due to pollutants at each stage of the production process. In agriculture, WF assesses the water used in crop production, which is crucial for optimizing irrigation and developing high-yield, low-water-use crops. Analyzing WF helps optimize farming, reduce water wastage, and promote sustainable food production. Additionally, by examining the WF datasets, one can even evaluate water scarcity by comparing the historical trends in crop water productivity and water consumption of the water-scarce region (Mialyk *et al.*, 2024). High WFs can indicate unsustainable practices, leading to environmental degradation,

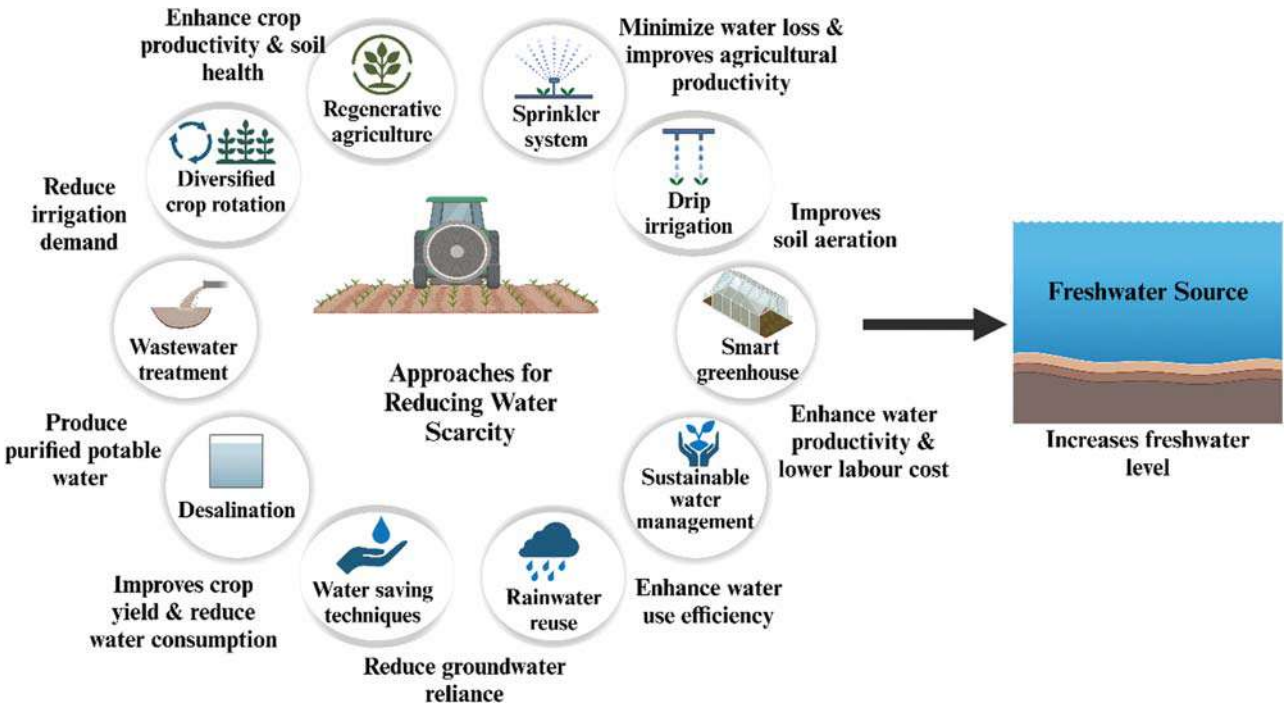


FIGURE 6.1 **Effective, sustainable practices for mitigating water scarcity in agriculture.**

such as depletion of aquifers, reduced flow in rivers, and negative impacts on ecosystems. Water footprint assessments (WFA) can offer valuable insights into water usage and pollution across economic sectors, identifying conservation and pollution control hotspots (Hoekstra, 2017). WF also help determine the magnitude of human impact on water resources and ecosystems, aiding in efficient water management and policy development, to facilitate more efficient allocation and use of water resources.

6.5.2 Distinguishing between green, blue, and gray water footprints

WF measures consumptive and degradative freshwater use and consists of three components, namely blue, green, and gray water footprints. The blue WF refers to the consumption of surface and underground water bodies used in the production process, including irrigation, industrial use, and domestic use (Castillo *et al.*, 2017). It measures the human impact on surface and groundwater resources, which are essential for meeting human needs but can lead to scarcity and environmental degradation if overused. It typically includes water in liquid flow form, stocked as runoff, and withdrawn from rivers, lakes, aquifers, and reservoirs through irrigation, industrial processes, and municipal drinking water supply systems. The green WF accounts for rainwater consumption, which encompasses evapotranspiration and water taken up by vegetation (Sardooi, Bazrafshan, and Jamshidi, 2024). Despite its significance, the green WF is often overlooked in discussions of water use. It is vital in rain-fed agriculture, where crops rely solely on rainfall and the water stored in the soil's root zone. The gray WF measures the volume of freshwater required for assimilating pollutants from industrial processes, household wastewater, and agricultural runoff. It serves as an indicator of pollution, highlighting the need for wastewater treatment to maintain water quality standards (Xu *et al.*, 2022).

6.5.3 Methodologies for calculating and interpreting water footprints

WFs involve various methodologies that address different contexts and purposes in water management, like water scarcity, pollution, and ecosystem impacts. One such approach is the Water Footprint Assessment (WFA), developed by Water Footprint Network (WFN), which is considered the most basic volumetric method used for calculating the WF. It sums the blue (surface and groundwater), green (rainwater), and gray (pollution) WFs and is generally represented by the equation (6.1) (Takawira, 2017):

$$\mathbf{WFtotal} = \mathbf{WFgreen} + \mathbf{WFblue} + \mathbf{WFgray}\ldots \tag{6.1}$$

The second approach is the impact-oriented WF, which combines volumetric methods with life cycle assessment (LCA) to evaluate the environmental consequences of water use. It considers water quantity and quality impacts on ecosystems and human health (Pfister *et al.*, 2017). The AWARE model, for instance, quantifies regional water scarcity impacts on ecosystems, human health, and natural resources (Boulay *et al.*, 2018). Additionally, out of many metrics, the water scarcity index (WSI) and withdrawal-to-availability ratio (WTA) are the two most globally applied standard water scarcity methods, which assess regional water scarcity by comparing water demand with water availability. WSI considers total water resources (TWR), water use efficiency (WUE), and domestic water proportion (PDW), as presented in equation (6.2) (Liao, 2024). WTA compares annual freshwater withdrawal (WU) to total available water resources (WR), as presented in equation (6.3) (Hybel, Godskesen, and Rygaard, 2015). It helps identify areas where water usage is unsustainable or where water resources are under stress.

$$\mathbf{WSI} = \frac{\mathbf{TWR} \times \mathbf{WUE} \times \mathbf{PDW}}{\mathbf{Number\ of\ Days\ per\ Year} \times \mathbf{Population}}\cdots \tag{6.2}$$

$$\mathbf{WTA} = \frac{\mathbf{WU}}{\mathbf{WR}}\cdots \tag{6.3}$$

In some cases, customized methodologies may be necessary to account for local water scarcity, quality, and socio-economic factors. These methodologies often involve stakeholder engagement and consider regional variations in water resources and usage patterns. For instance, groundwater footprint methodology was used as a policy tool for assessing both water quantity and quality at the aquifer scale in water-scarce regions (Kourgialas *et al.*, 2018).

6.6 Water footprint of global food production

6.6.1 Quantifying the water footprint of major food commodities

Quantifying the WF of major food commodities involves calculating the total freshwater used throughout all production stages, including growing, processing, and packaging. The Water Footprint Network (WFN) methodology is the most

common approach, encompassing green, blue, and gray water fractions. For instance, in the production and consumption of buffalo mozzarella, the WFN methodology can be used to calculate the total WF, which is the sum of the green, blue, and gray WF (Grossi *et al.*, 2024). Another approach to quantifying the WF is through field-data-based methods, which use climate, agricultural, and water usage data to evaluate the WF of food commodities at regional and national levels. For instance, in a study, the total WF of per capita consumption was calculated by adding the WFs of food and fuel wood, using data derived from the National Sample Survey for food and fuel wood consumption (Das, Gerbens-Leenes, and Nonhebel, 2021). Researchers have also used empirical models like AquaCrop, CropWat, and EPIC (Wang *et al.*, 2023), as well as regional water balance models like CropSyst, to quantify various levels of crop WFat low spatial resolution (Bocchiola, 2015). However, a new SWAT model has emerged, offering high spatial resolution in quantifying the WF of crop production based on hydrological processes (Janjić and Tadić, 2023). In another study, incorporating additional factors like the interaction of gray WF with white WF was used to assess the WF of cereals in Iran (Ababaei and Ramezani Etedali, 2017).

6.6.2 Regional variations and disparities in water use efficiency

Water use efficiency (WUE) refers to the effective utilization of water resources, influenced by factors like climate, water availability, agricultural practices, technology, economic development, and policies. Exploring these regional differences and the dynamic evolution of water resource utilization efficiency is essential for promoting high-quality, sustainable development of water resources. For instance, in China, a continuous decline in the utilization of agricultural water resources was observed from 2007 to 2018, with higher efficiency in the eastern region compared to central and western areas (Zeng *et al.*, 2023). This disparity was mainly due to the economic focus on secondary and tertiary industries and reduced agricultural employment. Increased rainfall and temperature also affect WUE. Arid and semi-arid regions in China have lower WUE due to low precipitation and less advanced agrarian technologies, while coastal, economically developed areas have higher WUE due to advanced technology and better management practices (Huang *et al.*, 2021). In contrast, regions like the Middle East and North Africa, despite using efficient irrigation techniques, face lower overall WUE due to limited water availability (Hejazi *et al.*, 2023). Enhancing WUE requires advanced irrigation technologies, preventing water loss, boosting economic growth, reducing pollution, and effective water management policies.

6.6.3 Implications for sustainable food production and consumption

Sustainable food production and consumption address global challenges such as climate change, resource depletion, and food security. Sustainable practices such as organic farming, agroforestry, and crop diversification reduce environmental impacts by lowering greenhouse gas emissions, conserving water, and maintaining soil health. These methods enhance biodiversity and resilience against climate change while reducing reliance on synthetic fertilizers and pesticides, thus improving farmers' livelihoods, particularly for smallholders (Wezel *et al.*, 2020). Sustainable food systems aim to provide fair access to nutritious food, support local food systems, reduce food waste, and promote zero hunger (Tekinbaş Özkaya *et al.*, 2021). Prioritizing local and seasonal produce and better meal planning can cut food waste and strengthen local economies. Adopting sustainable diets that emphasize plant-based foods and reduce meat consumption can improve health outcomes and lower environmental impacts (Béné *et al.*, 2019). These diets are nutrient-rich and linked to lower risks of chronic diseases. Additionally, grass-fed systems promote soil carbon sequestration, reduce eutrophication, and produce nutrient-dense beef, benefiting both the environment and human health (Clark and Tilman, 2017).

6.7 Water footprint for specific agricultural productions with energy purposes

6.7.1 Analyzing the water footprint of agricultural practices linked to energy production

The WF of bioenergy crops can be analyzed by assessing the water consumed for crop cultivation, irrigation practices, and crop impacts on water resources. For instance, a study using AquaCrop software on maize cultivation in northern China suggested that improving the harvest index, crop management, and water efficiency can reduce the WF and enhance bioenergy production (Zeng, 2023). Another study on maize-bioethanol production in Mexico found that optimizing green water use in rain-fed systems improves biofuel efficiency without affecting regional water availability or food prices (Hennecke *et al.*, 2016). This study employed a life cycle assessment approach, utilizing the Food and Agriculture Organization's (FAO) AquaCrop model to evaluate the WF through field water balances. The establishment of bioenergy crops, such as perennial grasses and short-rotation woody crops, offers opportunities for both successful eco-restoration of various marginal lands and energy production (Ranđelović and Pandey, 2023).

Moreover, using sugar or starchy crops such as sugar beet and sugarcane results in smaller WFs compared to oil-bearing crops for the production of bioenergy (Holmatov, Hoekstra, and Krol, 2019). These crops generally have lower water requirements than annual crops like corn and can be grown on less fertile land, reducing competition with food crops. Therefore, sustainable management practices and technological advancements are essential for balancing energy production with water sustainability, ensuring long-term environmental health and social well-being.

6.7.2 Case studies examining water use in biofuel and biomass production

Water use in biofuel and biomass production is a critical factor that varies significantly based on the type of feedstock, such as corn, soybeans, sugarcane, algae, and regional conditions. In a case study, a life cycle assessment (LCA) of bioethanol from hybrid poplar in the Pacific Northwest showed that the bioconversion stage used the most water (Morales-Vera *et al.*, 2022). Despite substantial irrigation needs, the overall net global warming potential was slightly negative due to carbon sequestration and displacement of fossil fuel use. In another case study, comparing the water use efficiency (WUE) of five perennial systems, including maize, in the US Midwest demonstrated that miscanthus had the highest WUE, followed by maize (Hamilton *et al.*, 2015). Perennial crops did not use more water than corn in rain-fed conditions, but expanding biofuel production in water-limited regions could have significant impacts.

Additionally, an optimization study of the water-energy nexus in biofuel production used a mixed integer, a multi-objective nonlinear model with the objectives of reducing the WF, elevating economic output per liter of water consumed, and energy output per liter of water consumed (Garcia and You, 2015). It found minimum WFs of 55.1 ML/year and varying economic and energy efficiencies per liter of water consumed. Another study assessed lignocellulosic perennial grasses under changing soil and water conditions in the Mediterranean (Scordia *et al.*, 2021). Giant reed showed higher CO_2 sequestration and lower environmental impact than miscanthus and responded better to reduced irrigation over time, while miscanthus required high water volumes for maximum yield.

6.7.3 Challenges and opportunities for integrating water and energy considerations in agriculture

Integrating water and energy considerations in agriculture provides several challenges and opportunities that are crucial for sustainable development. Agriculture, being a major consumer of water and energy resources used for the production of agricultural products, biofuel, biomass, and other processes like machinery, irrigation, and transportation, can lead to increasing competition for the availability of these essential resources. Notably, pumping, irrigation, treatment, and distribution systems will require significant energy inputs, and energy production can, in turn, impact water availability, leading to water scarcity, particularly in water-scarce regions (Tzanakakis *et al.*, 2020). Furthermore, variability in climate affects the future imbalance of both water availability and energy demand for irrigation, for enhancing agriculture water efficiency as well as supply variability. Due to the shortage of water, there is a need to minimize the reliance on fossil fuels for energy production, which can be done by integrating renewable energy resources (solar panels) into the agriculture sector, which can improve agricultural productivity, optimize water consumption, minimize costs, and improve water management (Agadi *et al.*, 2023).

Developing and maintaining efficient water and energy infrastructure can be quite expensive and technically challenging. However, by leveraging integrated water and energy management practices like developing dams or reservoirs for energy production, adopting advanced irrigation techniques can help increase resource efficiency, save costs, enhance sustainability, and reduce environmental impacts. Effective integration requires supportive policies and regulations. However, inconsistencies and gaps in policy frameworks often hinder the coordinated management of water and energy resources in agriculture.

6.8 Assessing water footprints: Methodologies and tools

6.8.1 Overview of methodologies for assessing water footprints

WFs are an applied tool to evaluate the effect of water-related utilization throughout the life cycle of products. The most common approach to assess the water life cycle analysis is through the water availability footprinting and through the assessment of released contaminant impacts (water degradation footprint). The important approach to evaluation is the midpoint methods, which use a characterization factor to quantify the effect of contaminated water. Another established method was the endpoint approach, which includes an indicator that measures the actual harm caused by an individual's or group's actions regarding the quality of the water in order to improve the process (Mikosch, Berger, and Finkbeiner, 2021).

6.8.1.1 Water Availability Footprint (WAF)

This technique uses functionality based on water quality criteria or Distance to Target (DtT) to measure water shortage resulting from contaminated water.

It is generally associated with the inventory to a desired value that is primarily a threshold value of water quality; if the DtT value is greater than 1, it shows an exceeding threshold value.

- Gray water footprint (Aldaya *et al.*, 2012; Hoekstra, 2011).
  The gray water footprint (GWF) is a component of the water footprint evaluation that was presented by Hoekstra (2011). It utilized the blue and green water footprint (WF). It also estimates the quantity of water required to dilute a contaminant to a specific quality level. The pollutant load L (mass/time) is divided by the threshold value $c_{i,\ max}$ (mass/volume), or the difference between the threshold and natural concentration ($c_{i,\ nat}$); I represents the pollutant.

$$\mathbf{GWF} = \frac{\mathbf{L_i}}{(\mathbf{c_{i,max}} - \mathbf{c_{i,nat}})}$$

- Pollution-induced water scarcity (Zeng, Liu, and Savenije, 2013).
  A method for incorporating the GWF (m^3) data into an evaluation of water shortage for a river basin was put out by Zeng, Liu, and Savenije (2013). The indices of pollution-induced water scarcity (I_{gray}) and water quantity scarcity (I_{blue}) in a basin, for calculation of water scarcity index (I), summed up ($I_{gray}+ I_{blue}$).

$$\mathbf{I_b} = \mathbf{I_{gray}} + \mathbf{I_{blue}}$$

- Water Impact Index (Bayart et al., 2014).

According to Bayart *et al.* (2014), it is suggested as a screening evaluation for water usage that takes pollution and consumption into account. The difference between the quantity of water extracted and Water Impact Index (WII) was evaluated and brought back to a body of water; both values increased by the corresponding water quality and shortage:

$$\mathbf{WII} = \sum_{\mathbf{i}} (\mathbf{W_i} * \mathbf{Q_{w,i}} * \mathbf{WSI_i}) - \sum_{\mathbf{i}} (\mathbf{R_j} * \mathbf{Q_{Rj}} * \mathbf{WSI_j})$$

where W (m^3) is the volume of water removed from a body of water, and R (m^3) is the volume of water returned to a water body; Q_W and Q_R (dimensionless) are the quality indices of the withdrawn and returned water, respectively; and WSI (dimensionless) signifies the water shortage index supplied by the Pfister, Koehler, and Hellweg (2009) model.

- The method of Boulay *et al.* (2011)

It relies on the functionality approach, which suggests that certain users may be unable to get water due to deterioration of water quality. In order to tackle this matter, water users include cooling, fishery, hydropower, transportation, and three residential, two agricultural, and one industrial user. This method is employed for quantification of the effects on the midpoint (Water Stress Indicator) and endpoint (health risk) levels:

$$\mathbf{Water\ Stress\ Indicator} = \sum_{\mathbf{i}} (\boldsymbol{\alpha}_\mathbf{i} * V_{i,in}) - \sum_{\mathbf{i}} (\boldsymbol{\alpha}_\mathbf{i} * V_{i,out})$$

where $V_{i,in}$ and $V_{i,out}$(m^3) are the volume withdrawn, and α is the dimensionless water stress index, with I representing the water type.

6.8.1.2 Water degradation footprint (WDF)

The effects of released contaminants spreading across the environment are calculated using this approach. It takes into account how ecosystems and people absorb contaminants with WDF combined with midpoint and endpoint approaches.

- Impact assessment models for water quality degradation
  It has been associated with the effects that come from consuming or coming into touch with contaminants. The life span estimate is based on ISO standards (ISO, 2006) life cycle assessment (LCA), which can be done at the midpoint, terminus, or both. The process consists of two parts: first, the fundamental flows (emissions to water)

gathered in the inventory are assigned to the appropriate effect categories (classification), and then they are multiplied by the respective characterization factors (CFs) (characterization):

$$\mathbf{I_c} = \sum_{\mathbf{p}} \mathbf{E_p} * \mathbf{CF_p}$$

where c represents the impact groups, p is pollutant, and E is emission.

While a wide range of environmental effects is taken into consideration in life cycle assessments (LCAs), only the impact categories related to water quality, such as aquatic eutrophication, acidification, aquatic ecotoxicity, and human toxicity, are taken into regard for the WDF.

The method of Ridoutt and Pfister (2013): A complete WF indicator that integrates quantitative and qualitative characteristics (WSF and WDF). They suggested utilizing LCAs models such as ReCiPE and incorporating them into "water-equivalent" units (Huijbregts *et al.*, 2017).

Pollution Water Indicator (PWI) (Lovarelli et al., 2018): GWF's limitations in evaluating water contamination were addressed by focusing on various kinds of contaminants. PWI evaluates the total pollution impact by combining WDF and other data. It is visualized as the area of a rectangle, with smaller regions signifying lower PWI values.

6.8.1.3 Water Scarcity Footprint (WSF)

WSF is useful for analyzing water quality, even though it is used mostly to measure water scarcity. It focuses insight into the lack of resources for clean water.

- Pollution-induced water scarcity

  The pollution-induced scarcity of water indicator was initially proposed by Zeng, Liu, and Savenije (2013), who developed GWF by accounting for local variations in effect evaluation. This adaptation ensures that GWF estimates are valid at regional sizes without going above resource thresholds by optimizing local freshwater availability. Such strategies frequently utilize approaches for assessing the impacts of water shortages and use.

6.8.2 Comparative analysis of different assessment tools and approaches

WFA focuses on two primary methodologies: impact-oriented assessment (which takes into account the environmental effects of water consumption) and volumetric evaluation (which quantifies blue, green, and gray water). Volumetric evaluation measures the influence on the environment and human health, whereas impact-oriented methods compare water supply to consumption. However, there are still hurdles that must be solved in order to establish uniform standards for sustainable water usage; life cycle impact assessments have made development in this area (Boulay *et al.*, 2011; ISO, 2006; Hoekstra, 2011, 2017). The assessment of water footprints considers the effects of pollution on water supplies, social health, and the environment (Pierrat *et al.*, 2023). Gray water footprinting may be harmful since it disregards local water restrictions. Based on water quantity and quality, the WII assigns a single score (Mikosch, Berger, and Finkbeiner, 2021). While WFA takes into account the footprints of green, gray, and blue water, LCA focuses on blue water. In addition, LCA evaluates net green water changes generated by alterations in vegetation, which may result in net negative footprints (Wang *et al.*, 2021).

According to Boulay *et al.* (2011), the WDF takes a functionality approach, implying that contaminants beyond water quality thresholds have an impact on water functioning. WDF-based models need extra WSF computation for pollution consequences, in contrast to the DtT technique. On the other hand, WAF-based methods make outcomes easier for stakeholders to understand by combining pollution and water consumption into a single score. WDF offers a more comprehensive effect evaluation. However, water usage should be taken into account in the WAF to prevent double counting; this might be done by adding the WSF to the WAF findings (Mikosch, Berger, and Finkbeiner, 2021) (Table 6.1). Models that assess the effects on water quality generate information for several impact categories rather than a single score.

6.8.3 Practical considerations for conducting water footprint assessments at global and local scales

Addressing essential elements is necessary for conducting evaluations of the global water footprint (WF). All commerce and consumption operations were initially included in the national WF accounts, which emphasized accounting records

TABLE 6.1 Reviewed and compiled methods used for assessing water footprints.

Methods	Water footprint type	Formula	Pollutant coverage	Inventory requirement	Regionalization	Result consequences after applying these methods
GWF (Hoekstra, 2011)	WAF	$\mathbf{GWF} = \frac{\alpha_i * \mathbf{Appl_i}}{(c_{i,max} - c_{i,nat})}$	Low	Emissions of pollutants to water	–	Selected threshold
Pollution-induced water scarcity (Zeng, Liu, and Savenije, 2013)	WAF	$\mathbf{I_{gray,b}} = \frac{\mathbf{GWF_b}}{\mathbf{Q_b}}$	Low	Emissions of pollutants to water	Yes, based on water scarcity	Selected threshold
Water Impact Index (WII); (Bayart *et al.*, 2014)	WAF	$\mathbf{WII} = \sum_i (\mathbf{W_i} * \mathbf{Q_{w,i}} * \mathbf{WSI_i}) - \sum_i (\mathbf{R_j} * \mathbf{Q_{Rj}} * \mathbf{WSI_j})$	Low	Emissions of pollutants to water and water flows	Yes, based on water scarcity	Selected threshold
(Boulay *et al.*, 2011)	WAF	$\mathbf{Water\ Stress\ Indicator} = \sum_i (\alpha_i * \mathbf{V_{i,in}}) - \sum_i (\alpha_i * \mathbf{V_{i,out}})$	High	Emissions of pollutants to water and water flows	Yes, based on water scarcity	Pollutants included in the inventory, WSF
Water Degradation Footprint	WDF	$\mathbf{I_c} = \sum_p \mathbf{E_p} * \mathbf{CF_p}$	High	Emissions of pollutants to water	Yes, based on cause-effect chains	Pollutants included in the inventory
Method of Ridoutt and Pfister (2013)	WDF + WSF	–	High	Emissions of pollutants to water and water flows	Yes, based on cause-effect chains	Pollutants included in the inventory
Pollution Water Indicator (Lovarelli *et al.*, 2018)	WDF + WAF	–	High	Emissions of pollutants to water	Yes, based on cause-effect chains	Pollutants included in the inventory

GWF: Gray water footprinting; WAF: Water availability footprinting; WDF: Water degradation footprinting; WSF: Water scarcity footprinting.
Adapted from Mikosch N., Berger M., Finkbeiner M., 2021. Addressing water quality in water footprinting: current status, methods and limitations. Springer Sci. Business Media Deutschland GmbH, Germany. Int. J. Life Cycle Assessment. 157–174.

and consumption up until 2008. Later, as commercial interest in bringing the WF idea up to global standards developed, the scope was extended to include production.

This resulted in the emergence of the Global WFA Standard by the Water Footprint Network (WFN) (Hoekstra, 2017). It is divided into four stages: response formulation, accounting, sustainability evaluation, and scope selection. Comparing WFs to reference levels puts into perspective them in terms of equality, efficiency, and sustainability. The guideline places a strong emphasis on water security and the significance of evaluating supply networks' dependency on unsustainable water consumption. WFs are going to be assessed more and more in combination with consumer preferences, corporate policies, investment guidelines, product labeling, trade agreements, global cooperation, and environmental factors (Hoekstra, 2017).

Local WF studies emphasize internal and external use and frequently concentrate on output within river basins (Hoekstra, 2017). These studies, which focus on local solutions and effective water usage, usually overlook supply connections in their efforts to address regional water problems. When demand exceeds supply, poor practices can deteriorate the quality of the water and result in shortages. Local water problems are frequently brought on by global processes, such as India's irrigation or Bangladesh's cotton processing improper use. Water-use efficiency has been highlighted by WF research from the perspectives of local production, global trade, and consumers (Chukalla, Krol, and Hoekstra, 2015). Every nation has unique regional strategies that are developed to address issues that are peculiar to that nation and are related to it locally.

6.9 Factors affecting water footprint

6.9.1 Identifying key factors influencing water footprints in agriculture

A number of parameters, including water-saving irrigation, crop layout, crop economics, fertilizer usage, and water delivery infrastructure, affect how efficiently agricultural water is used. Important structural and economic factors are crop planting ratios and income levels (Wang *et al.*, 2023). The preservation and supply mechanisms are influenced by irrigation techniques and chemical contamination, among additional impacts on the environment.

Several key factors that impact the WFs in agriculture sectors are as follows: water-efficient irrigation techniques optimized for crops, soil, and climate, such as drip irrigation and sprinkler systems (Azadi *et al.*, 2022; Chukalla, Krol, and Hoekstra, 2015). The proper use of fertilizers and pesticides is essential for both agricultural productivity and environmental sustainability. Strict controls, precision farming, and integrated pest management have been emphasized (Barłóg, Grzebisz, and Łukowiak, 2022). Crop selection and control of water demand, taking drought-tolerant varieties, crop water requirements, suitability, and rotation into account (Suruliandi, Mariammal, and Raja, 2021; Kulkarni *et al.*, 2023) (Figure 6.2). Some other key factors that influence WF in the agriculture sector are land use changes and technology and innovation in agriculture as hydroponics, precision farming, and genetically modified crops with drought tolerance.

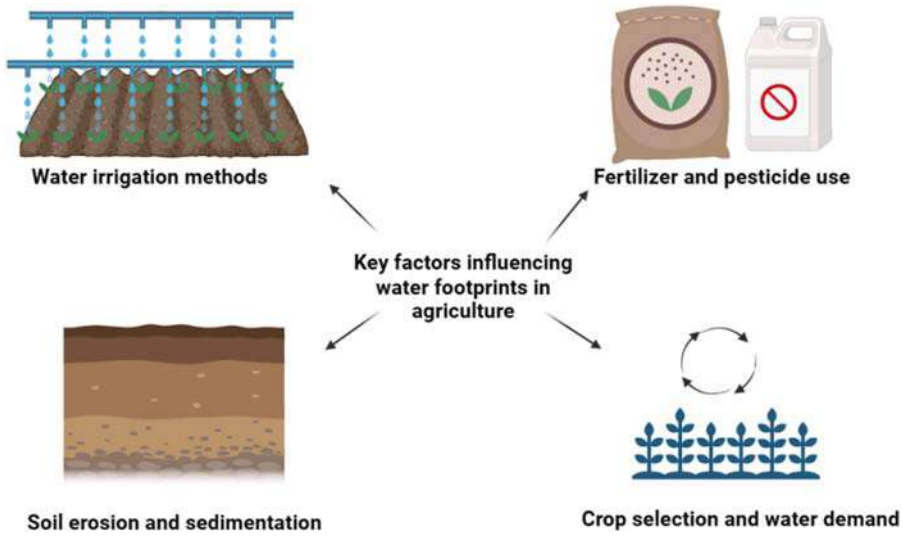


FIGURE 6.2 Key factors impacting water footprints in agriculture.

6.9.2 Socioeconomic, environmental, and technological determinants

Numerous studies have shown that achieving the water security sustainable development goals (SDG 6) supports other SDGs. At the same time, failure leads to poor health, ecosystem collapse, food and energy insecurity, and potential conflicts in water-deficit areas (Nkiaka, 2022).

Numerous socioeconomic, environmental, and technical factors must be taken into account in order to accomplish SDG 6 (van Beek and Lincklaen Arriens, 2014). The main variables in socioeconomics are urban population, good governance, official development assistance for water and sanitation services (ODA-WSS), and environmental determinants such as water availability, climate risk, and ecosystem vitality. In technological factors, the key factors are water resource management (WRM) and integrated water resources management (IWRM) (Table 6.2).

TABLE 6.2 Several factors, including socioeconomic, environmental, and technical ones, have an impact on the water footprint.

Water security components	Factors	Description	Source of data
Socioeconomic Determinants	ODA-WSS	Investments in sanitation services and water infrastructure impact water security. Insufficient financing can improve water supply and lessen traces.	(www.data.worldbank.org)
	Gross Domestic Product (GDP) per capita	Patterns of water usage are impacted by economic affluence. Increased water demand for home, agricultural, and industrial operations is frequently correlated with higher GDP levels. It is beneficial to prevent the agricultural water deficit by industrial restructuring.	(www.data.worldbank.org); (Wang, Su, and Zhang, 2022)
	Percentage of Urban Population	Urban regions have dense populations, and industrial activity typically results in greater water footprints. Urban environments have concentrated water requirements that affect both indirect and direct usage. Increased impervious surfaces from urban development can have an impact on groundwater recharge and water penetration.	(www.data.worldbank.org); (Nkiaka, 2022)
	Good governance	Water footprints are mostly determined by the governance frameworks and effective water management regulations that are in place. Water consumption is impacted by clear legislation and effective allocation systems. It optimizes water resource management and control using a regionally integrated management system.	(Nkiaka, 2022; Wang, Su, and Zhang, 2022)
Environmental Determinants	Water Availability	Freshwater resources' natural availability directly impacts water footprint resources. Estimates of the total annual renewable water resources per capita, which include groundwater and renewable surface water resources accessible in each nation, are used to evaluate the availability of water.	(Nkiaka, 2022)
	Climate Risk	Water stress driven by climate change has a significant impact on water footprints, and it leads to drought, sea level rise, and an increase in extreme climate.	(Babel *et al.*, 2020)
Environmental Determinants	Water resource management (WRM), Integrated water resources management (IWRM)	WRM, one of the SDG6 aims, encompasses the various social and political facets of water security, such as water governance, legislation, institutional and human capacity, and funding.	(UNEP, 2018)

Adapted from Nkiaka, 2022.

Water footprints (WFs) provide information on the global aspects of good governance as well as the patterns of water utilization (Senthil Kumar and Grace Pavithra, 2019). In conclusion, tackling WFs necessitates a comprehensive strategy that takes into account environmental, technical, and socioeconomic aspects. It may strive toward a more water-secure future by encouraging sustainable habits, education, and investment in water-related technology.

6.9.3 Implications for policy and management interventions

Assessments based on the good's water footprint (WF) in relation to benchmark levels and the sustainability of the water sources used in its components would make a water label more useful. A single water footprint number (WF number) is not as useful as a full WFA for directing firm strategies and policies. Businesses should report on their progress in lowering WFs in unsustainable regions, according to the Dutch environmental ministry. Nowadays, a lot of companies, as well as governments, understand the importance of WFA. In order to assist with water management, the UK, for instance, carried out a WFA for Hertfordshire and North London (Zhang *et al.*, 2014). WFA has been incorporated into national water policy in Spain and India (Aldaya, Martínez-Santos, and Llamas, 2010). WF figures need to be evaluated extensively (Hoekstra, 2017). Although Jordan imports rice and wheat to reduce its WF, it still has serious water problems because of unstable supplies, groundwater depletion, and regional wars (Salameh, Alraggad, and Harahsheh, 2021).

An integrated, multidisciplinary approach is necessary to address these issues. Policies, including water pricing, rights, and markets, can encourage local, sustainable consumption and allocation (Debaere *et al.*, 2014; Dharmendra Kumar Singh *et al.*, 2023). India's national water policy, which was amended in 2002 and 2012, promotes stakeholder engagement and sustainable practices while promoting integrated water resources management, demand management, and conservation (Kathpalia and Future, 2002; K. Singh et al., 2023). Sustainable distribution, waste reduction, and water conservation are the three main objectives of the national water mission (Shrestha and Mishra, 2021). Political will and institutional capability are obstacles to executing policy. Water awareness and multi-stakeholder participation are necessary for effective policy (Katyaini and Barua, 2016). WFA assists in reducing water-intensive industrial operations, choosing water-efficient crops and irrigation methods, and putting water reuse technology into practice. For identifying hotspots, precise information on pollution and utilization of water is crucial (Mehla *et al.*, 2023).

6.10 Decreasing water footprints through precision agriculture

6.10.1 Exploring the role of precision agriculture in reducing water footprints

A key strategy to sustaining expanding urban populations sustainably is precision agriculture. When applied to urban agricultural settings, precision agriculture targets treatments using data and technology. Precision farming has become a trailblazing strategy as urban areas grow, marking a major shift from conventional agriculture methods to more specialized, data-driven tactics (Addas, Tahir, and Ismat, 2024). Precision agriculture is a farming method that maximizes crop yields, reduces waste, and boosts production by using cutting-edge technology and data analysis. It is a possible tactic for addressing some of the most important problems facing modern farmers with the advent of GPS (global positioning systems), GISs (geographic information systems), yield monitors, and other data generators in all three critical phases of agricultural operations in the 1990s, and agriculture has the potential to feed a growing global population while reducing environmental effects (Liu *et al.*, 2021; Trivelli *et al.*, 2019).

The development of precision agriculture through advancements in farming reduces the need for operational inputs like pesticides and fertilizers, which mostly affects the gray water footprint. On the other hand, when comparing the identical approaches handled with uniform rate application, precision agriculture resulted in an average increase in crop output. In a study demonstrated by Borsato *et al.* (2018), precision agriculture uses less water when compared to traditional tillage, particularly when using conservative tillage. In recent years, crop farms (CF) may be transformed by artificial intelligence (AI)-powered precision agriculture to improve nutrition, food security, and environmental sustainability. In past years, the development of a robotic prototype for crop health monitoring (CF) leveraged deep reinforcement learning to optimize crop upkeep, watering, and planting based on real-time sensor data. The system was benchmarked, and the findings showed a 41% drop in water consumption, a 33% decrease in pesticide use, and a 26% increase in crop output (Addas, Tahir, and Ismat, 2024).

6.10.2 Technologies and practices for optimizing water use efficiency

Precision farming requires making data-driven management choices that maximize resource utilization, decreasing the negative effects of agriculture on the environment while also reducing expenses. In order to collect actual data, smart technologies, or ICT (information and communication technology), were integrated into agricultural gear and devices.

Here, robotic technologies, remote sensing technologies, drones, autonomous cars, global positioning systems (GPS), telematics, automated hardware, and software were integrated into farming methods to collect data on crops and soil conditions (Monteiro, Santos, and Gonçalves, 2021). In recent times, image analysis has emerged as a more dependable data source than expensive, time-consuming, manual data collection techniques (Saranya *et al.*, 2023). Machine vision (MV) technologies have previously been effectively used to identify crop species. Weed, disease, and crop stress detection, as well as agricultural seed quality evaluation, are still at the prototype stage. In order to create intelligent robots for multispectral imaging analysis and real-time analysis in field variable rate applications, new deep learning (DL) approaches in developing machine learning (ML) technologies are now combined with MV applications (Karunathilake *et al.*, 2023).

The Internet of Things (IoT) describes a system of linked objects and technology. The precision agriculture data gathered using IoT architecture for agriculture includes agricultural sensors with ICT and UAV. The improvements in wireless networks and communication technologies have expanded the IoT's applications in a variety of industries, including higher-throughput phenotyping and real-time remote control, along with improved coverage, bandwidth, connection density, and end-to-end latency (Liu *et al.*, 2021). With the development of sensors with independent intellectual property rights and smart devices like intelligent tractors, uncrewed aerial vehicles, and robots that can replace high levels of manual labor input and perform high-quality operations, the IoT can be widely used in all areas of precision agriculture (Saranya *et al.*, 2023).

Artificial intelligence (AI) offers significant promise for reducing food waste, enhancing production cleanliness, and monitoring machinery throughout several agricultural phases, including supply chain and agrarian production patterns and the management of the soil, crops, and water, as well as the prevention of disease and pests in the agricultural production process (Karunathilake *et al.*, 2023). Blockchain technology, primarily used in cryptocurrency, is a decentralized, distributed database that keeps an ever-expanding list of ordered entries or blocks. The data openness, immutability, and dependability provided by blockchain enhance the confidence across different supply chain participants. Schedules for irrigation, water sharing, energy use, and the integration of labor and machinery may all be better planned (Sendros *et al.*, 2022). The high-throughput phenotyping (HTP), which includes drones, sensors, and artificial intelligence, may be used to enable more precise and efficient phenotyping, which will help breeders uncover desirable characteristics and make better selections about inputs like water, fertilizer, and pesticides to boost productivity, cut waste, and enhance output (Guo *et al.*, 2021).

6.10.3 Case studies demonstrating successful implementation of precision agriculture techniques

It is believed that the concept of integrating observation sensors and agricultural machinery to generate big data will continue to be crucial for farming innovations in the future. Precision farming utilizing IoT technology seeks to minimize environmental effects while improving crop yield and revenue in Japan. Decision support systems, variable-rate technologies, and descriptions of variability are examples of key technologies. The effort and area of paddy fields per farmer have grown over the past 20 years despite a 34% decline in the number of rice farmers (Yagi, 2016). To standardize smart agriculture, the Smart Agricultural Machinery System (SAMS) combines geolocation data with field conditions (Rokhmana, 2015).

Robotics with autonomy has been effectively applied in Israel. With the development of AI-powered flying robots for fruit picking, Tevel Aerobotics Technologies was able to reduce labor shortages and production expenses by 30% while also offering real-time updates through a mobile app. Global application of this technology is expected to improve the area of agricultural robotics (Karunathilake *et al.*, 2023).

An 83% success rate in harvesting tomatoes in 12 seconds per bunch was attained by Beijing Research Center's cherry tomato harvesting robot for greenhouses (Feng *et al.*, 2014). In order to improve efficiency and precision in seed sowing, Jin *et al.* (2019) developed a small-sized vegetable seed electric seeder using optical fiber sensing technology.

Another technology was demonstrated by Aasim *et al.* (2022) to optimize tissue culture procedures using machine-learning algorithms with in vitro regeneration for common beans. The researchers from Malaysia's University Tenaga National exhibited autonomous robots that spray fertilizer and pesticides. One such robot is a low-cost agricultural robot that is used for crop monitoring and treatment (Ghafar *et al.*, 2021), Hadi Ishak *et al.* (2023) developed an automated organic fertilizer mixer technology, which is based on IoT, with the goal of lowering labor costs and increasing efficiency.

6.11 Conclusion

This book chapter deals with the multifaceted role of water in the agriculture sector by highlighting the intrinsic value of water, its economic implications, and global importance. Water plays a vital role in agricultural production as well as acting

as the key factor in maintaining the health of the agricultural ecosystem. However, the increasing population trend throughout the globe creates a high demand for water. Therefore, proper and sustainable water management and practices are the ultimate need. In this era of instruments, there is a need for innovative and applicable technologies for the appropriate adoption of integrated water management strategies that consider the ecological, economic, and social dimensions of water use. For this, different innovative technologies, integrated water management practices, scientific policies, formation of education capacity building, and development of climate adaptation strategies should be adopted.

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Part II

Environmental impact and ecological considerations

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Chapter 7

The ecological footprint of agricultural waste: Pollution and greenhouse gas

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Chapter Outline

7.1. Introduction 101
7.2. Comparative analysis of agricultural practices 102
7.3. Agriculture waste pollution: Measurement and impact 104
7.4. Greenhouse gas emissions in agriculture: Sources and dynamics 106
7.5. Methodologies for ecological footprint calculation 111
7.6. Technological innovations in shaping ecological footprint reduction 112
7.7. Challenges and future considerations 113
7.8. Conclusion and recommendations 116
Acknowledgment 117
References 117

7.1 Introduction

Agriculture is the mainstay factor of economic prosperity and livelihood on one hand. In the last few decades, the globe's population has increased from 3.7 billion in 1970 to 7.9 billion in 2021 and is predicted to rise to 9 billion by 2050 and to 11 billion by 2100, respectively (Koop and van Leeuwen, 2017). In a world with delimited resources, it is always an ominous challenge to guarantee food security in the years to come. It is highly expected that global food security will double in folds by the beginning of the next century. To fulfill the extensive demands of feeding millions, there has been a significant rise in crop production synchronized with fostered industrial activities and technological development, which has further contributed toward the generation of large quantities of agro-waste every year. The utilization of high-yielding crop genotypes, irrigation systems, chemical fertilizers, pesticides, and other innovations in agricultural systems has led to increased waste pollution and greenhouse gas emissions (GHG). This in turn can adversely affect human health while putting at risk the sustainability of ecosystems and natural resources (Beillouin *et al.*, 2021). Based on the latest statistics, 2.01 billion tons of municipal solid waste were generated globally in 2016. Meanwhile, only a small fraction of this was managed as useful resources. This figure is expected to increase to 3.4 billion tons by 2050 (Kaza *et al.*, 2018). Thus, the inadequate management of these waste products causes pollution and results in major health and environmental issues. It could cause groundwater contamination, soil pollution, and GHG in the atmosphere. Increased GHG in terms of carbon dioxide (CO_2), methane (CH_4), and nitric oxide (N_2O) is closely linked to global climate change (Li *et al.*, 2024). This

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potentially denotes a massive loss of resources, which contradicts the concept of sustainable development that aims to meet the necessities of the current generation without devastating the resources for the next generations.

The term "ecological footprint" (EF) was primarily introduced in 1998, at the University of British Columbia, in Canada, by Wackernagel and Rees (1998). EF is a synthetic term of environmental sustainability, applied to evaluating humanity's impacts on the environment and has been used to highlight both the apparent unsustainability of current practices and the inequalities in resource consumption between and within countries. The crucial role of human beings in the climate crisis has been acknowledged also in the scientific arena, beginning from Paul Crutzen (McNunn *et al.*, 2020), who introduced the term "Anthropocene" to represent human responsibility in affecting the current ecological unbalance (McNunn *et al.*, 2020). The EF is calculated by measuring the area of land and water ecosystems required to produce the resources consumed and to absorb the emissions produced by a specific population in a given area. For development to be considered sustainable as outlined in the 1991 report "Caring for the Earth" (adapted from Nkiaka, 2022). by UNEP, WWF, and IUCN, it must' support ecosystems in regenerating the necessary resources consistently, ensuring human well-being through natural processes. The ecological footprint (EF) is a vital metric that estimates the biologically productive land and sea areas needed to provide the renewable resources consumed by a population and to absorb its waste, using current technology and resource management practices. The EF encompasses various types of productive areas, including croplands: required for the production of food and fiber, grazing lands: used for the production of animal products, forested areas: needed for the production of wood products, marine areas: utilized for fisheries, built-up land: allocated for housing and infrastructure, and forested land: necessary to absorb carbon dioxide emissions from energy consumption. EF is measured in "global hectares" (gha) and can be calculated at different scales, such as for individuals, regions, countries, and globally. Additionally, it can determine the available productive area, or biocapacity, which helps in understanding the balance between resource demand and supply (Guo *et al.*, 2017). Knowledge of ecological footprints allows giving more detailed information about the rate of resources exploited during the production chain and their impact on the environment. As we continue to understand the ecological footprint of agriculture waste better, it is important to choose the appropriate agriculture system and practice that controls waste pollution and GHG emissions along with achieving sustainability.

The focus of this book chapter is to discuss the ecological footprint of agricultural wastes and its consequences concerning pollution and gas emissions and how to combat the challenge to achieve sustainability balanced with reduced GHG on a global scale.

7.2 Comparative analysis of agricultural practices

7.2.1 A comparative overview of traditional vs. sustainable agriculture

Greener farming is an innovative concept for the development of a sustainable agriculture system that is more productive with less waste and gas emissions. Over the last decades, the agriculture sector has witnessed many promising transformations in terms of plant domestication, adopted crop rotation techniques, breeding programs, and the broad use of organic fertilizers and pesticides also instigated as a green revolution. The traditional agricultural production systems tend to attain global food security in the setting of rising demands and the overexploitation of natural resources, which makes it essential to reconsider existing production systems concerning the turning to more sustainable systems. Traditional agriculture depends on the use of monocrops, synthetic chemicals, and fossil fuels. However, in agriculture, sustainability means going forward with the natural models and resources that farms employ. Among other things, sustainable agriculture includes rotating crops, implementing biodiversity, introducing cover crops, limited till systems, integrated pest management, an amalgamation between crops and animal farming, agroforestry practices, and precision farming (Rehman *et al.*, 2022). In addition to these practices, conventional varieties are also improved following regional stress of the environment like drought, cold, and salinity. The main aim of sustainable agricultural policies is to ensure environmental sustainability while maximizing farm productivity (Shah and Wu, 2019). Hence, sustainable agriculture has emerged as a modern alternative to conventional agriculture, given its ability to simultaneously curtail GHG emissions while challenging food production and emphasizing climate resilience (Muhie, 2022). Thus, agriculture is increasingly becoming serious about the summit Paris Agreement's global emissions reduction aims and reaching net-zero emissions, involving the Sustainable Development Goals.

7.2.2 Contrasting different ecological legacies from different farming methods

Agriculture is the second largest contributor to GHG emissions by around 15% after the energy sector (68.1%) (Lamb, 1990). It is anticipated that CO_2, N_2O, and CH_4 emissions from the agriculture sector will expand by 2030, which could severely affect climate, water and soil pollution, and biodiversity (Aryal *et al.*, 2022). In addition, agricultural production

also discharges emissions from the energy use of input supplies, such as fertilizers, agrochemicals, irrigation, and farm machinery. Thus, enhancing agricultural activities and input use efficacy in food production can significantly contribute to decreasing the ecological footprint of agricultural waste and gas emissions (Amelung *et al.*, 2020). Multiple practices can lessen GHG emissions and also boost the efficiency of resource use and create synergy with rural development and food security goals. Agroforestry is a type of practice that achieves nine of the Sustainable Development Goals such as reduced GHG, soil fortification, enhancements in air and water quality, and biodiversity benefits (Khatri-Chhetri *et al.*, 2023). Sustainable soil management facilitated by conservation tillage and cover crops is another important approach that decreases soil erosion, lessening the use of fossil fuels and mechanical effort while preserving soil quality (Farmaha, Sekaran, and Franzluebbers, 2022). Moreover, unsuitable irrigation systems exert methane emissions and salinization; hence, smart irrigation systems can reduce these harmful environmental impacts while increasing food productivity. Various crop divergence practices are also important for enhancing biodiversity and enhanced ecosystem services. For instance, they improved water and soil quality as well as achieved effectual pest and disease control (Beillouin *et al.*, 2021). While we discuss the ecological legacies of different farming methods, it is important also to observe the role of excessive utilization of synthetic fertilizers in the deterioration of environmental management, specifically for water resources. Reports have exposed that crops can use only 30 to 50% of inorganic fertilizers and discharge the leftover wastes into the soil, where it contaminates groundwater. However, sustainable agriculture that allows the use of organic fertilizers like crop residues, farmyard and organic manure, and compost accompanied by integrated pest management seems to be more balanced to decrease the rates of environmental pollution. It appears that the new scientific methods and inputs in the sustainable agriculture system are productivity-oriented and provide a promising opportunity to promote environmental resilience while offering the benefits of reduced waste and GHG emissions.

7.2.3 Contrasting ecological footprints in different geographic regions

7.2.3.1 Africa

It has been reported that Africa has shown increasing exploitation of resources over the years, at a rate faster than their capacity to be regenerated, although the EF per person is below Western standards and the world average. It has been shown that the total ecological footprint (EF) and biocapacity (BC) have both increased over the years, with values of about 1.513 and 1.288 million gha in 2018, respectively, while at the per capita level, an average EF of more than 1 gha/person is observed over the years (about 1.35 gha in 2018), compared with a reduction in per capita biocapacity from about 4.32 gha/person in 1961 to about 1.15 gha/person in 2018. Compared to the largely unchanged impact of each single inhabitant of the continent and a slightly increasing total BC, due to the steadily increasing population trend, the total EF has increased significantly, and there has been a steady and rapid decrease in per capita BC.

The total EF trend has increased from about 324.1 Mgha in 1961 to about 1,513.5 Mgha in 2018. It can be seen that the largest EF is associated with cropland and CO_2 uptake land, followed by EFs associated with forest land and grazing land. Over the same period, the EF of fishing grounds has remained essentially unchanged. In terms of biocapacity (productive land area), on the other hand, a decrease can be observed from about 936.8 Mgha in 1961 to about 1,288 Mgha in 2018, with three main contributions from cropland, forest land, and grazing land. In detail, compared to 1961, the BC of cropland appears to have decreased by about 5%, the BC of fishing grounds by about 81%, the BC of forest land by about 83%, while the BC of grazing land has dropped by about 79%. For a long time, Africa was characterized by a situation of "ecological surplus," but its margin of available biocapacity has gradually dwindled, to the point that it now finds itself in a condition of "ecological deficit," which means that demand now beats supply (the EF exceeds the BC). This situation is largely due to population growth and the consequent need to meet its ever-increasing demands—that is, a situation in which the increasing biocapacity (mainly due to growing agricultural production) has not kept "in step" with the increase in demand. However, the biocapacity of the African continent is also used for producing natural resources, which are exported, legally or illegally, and a part of this biocapacity is included in the global common resources that, for example, are used for capturing carbon dioxide (Network, 2012). Furthermore, the increased biocapacity could have occurred at the expense of other impacts, for example, in terms of the WF, as an increase in productive cropland could be associated with the conversion of ecologically less productive land to growing crops, resulting in greater use of water (but also energy) resources, which means that it is necessary to assess this indicator as complementary to the WF, in order to paint an overall picture of how the situation is developing in terms of impact/sustainability.

7.2.3.2 Asia

Although the per capita EF is below the Western standards and the world average, the available data of Asia has exhibited increasing exploitation of resources over the years, at a faster rate than their capacity to be regenerated. The total EF and BC

have both increased over the years, with values of 10,774 and 3,317 million gha in 2018, respectively, while at the per capita level the EF has increased from about 1 gha/person in 1961 to about 2.45 gha in 2018, compared with a reduction in per capita biocapacity from about 1.06 gha/person in 1961 to about 0.75 gha/person in 2018 (Italian Agency for Development Cooperation AICS, 2024). The data point to a situation in which the impact of single inhabitants of the continent is clearly growing (probably as a result of changing lifestyles), and consequently, the total EF is increasing even more so also as a result of population growth. Conversely, compared to a slightly increasing total BC, there has been a steady decrease in per capita BC due to population growth (Italian Agency for Development Cooperation AICS, 2024). The total EF increased from 1,576 Mgha in 1961 to 10,774 Mgha in 2018. In terms of the contribution of the six components, the largest EF is associated with CO_2 uptake land, followed by cropland and smaller contributions from the other EFs; all the components have increased over the years. However, biocapacity an upward trend was recorded from about 1,713 Mgha in 1961 to about 3,317 Mgha in 2018, with the main contribution from cropland, followed by forest land. In terms of per capita BC, a more or less significant decline is denoted for different BC components (Italian Agency for Development Cooperation AICS, 2024). In the Asia-Pacific countries, the gap between EF and BC is enlarged, leading to increasing demand for natural resources at a faster rate than the environment's capacity to replenish them. Although there is a clear variance between different countries, with most of the EF associated with just a few countries (China, Japan, India, and Indonesia), this situation can be attributed to a population growing at a faster rate than BC, but also to a rising new middle class and related lifestyle developments, which are boosting the demand for the energy, food, metals, and water needed to provide for ever-increasing needs (Network, 2012). Although the "ecological deficit" is common to all regions, in fact, in some of them the gap is widening at a faster rate than in others (Italian Agency for Development Cooperation AICS, 2024).

7.2.3.3 Latin America and the Caribbean

The available data for Latin America and the Caribbean region exhibited that the EF per person is in the queue with Western standards and the world average, with a general trend of resource exploitation enhancing at a faster rate than the capacity of resources to be regenerated, although there is still a situation of "ecological surplus." The total EF is clearly increasing (about 1,504 Mgha in 2018), and the total BC has remained basically unchanged over the years (about 3.094 Mgha in 2018), while the per capita EF has improved from 2.31 gha/person in 1961 to 2.47 gha/person in 2018, relative to a decrement in per capita BC from about 14.13 gha/person in 1961 to about 5.08 gha/person in 2018. Thus, the total EF has enhanced significantly, and there has been a steady and rapid decline in the per capita BC, relative to observable increase in the effect of each single inhabitant of the continent (which may be due to changes in lifestyle) and a substantially stable total BC, due to population growth. The total EF trend increased from 494.56 Mgha in 1961 to 1,504 Mgha in 2018. In terms of the contribution of the six components, the largest EF by far is related to CO_2 uptake land, cropland, and important contributions from forest land and grazing lands. Moreover, there has been an increase in all the components over the years. On the other hand, biocapacity has mainly remained unchanged, from about 3,018 Mgha in 1961 to about 3,094 Mgha in 2018, with the main contribution associated with forest land, followed by cropland, grazing land, and fishing grounds. In terms of per capita BC, there is a significant decrease in the BC of forest land, fishing grounds, and grazing land, while the BC of cropland and, in accordance with methodological assumptions, the BC related to built-up land have increased EF. While South America is currently in line with the above descriptions, that is, in a situation of "ecological surplus," albeit diminishing over time, the other regions (the Caribbean and Central America) show a rather different picture (Italian Agency for Development Cooperation AICS, 2024).

7.3 Agriculture waste pollution: Measurement and impact

7.3.1 Types of agriculture waste

A vast array of agricultural residues, stemming from farming and related activities, includes a heterogeneous mix of byproducts containing significant quantities of carbohydrates, cellulose, lignin, hemicellulose, and starch. Crop residues such as leaves, stalks, and husks from crops such as rice, wheat, corn, and sugarcane, animal manure, agro-processing wastes (i.e., fruits and vegetable peels), food waste, silage, green waste (organic matter such as grass clippings, tree trimmings, and garden waste), and bioenergy crops (i.e., switchgrass, miscanthus, and willow grown specifically to produce biofuels like ethanol and biodiesel) are all common types of agricultural waste, as are pesticide containers and packaging. Medina *et al.* (2015) revealed how proper disposal of these residues might result in favorable outcomes such as single-cell proteins, methane, and chemical molecules.

7.3.2 Quantifying types and volumes of agricultural wastes

Overall, agricultural residue and organic waste are important components of the worldwide agricultural business. China is the world's greatest producer of agricultural waste (Koul, Yakoob, and Shah, 2022), owing to its extensive agricultural

activity and large rural population. The inadequate disposal of these wastes can hold severe environmental and health marks. According to Lei (2022), the annual production of agricultural straw, animal and poultry manure, and agro-processing residue is significant in China, with estimates reaching 9.8×10^8 t of straw, 3.8×10^9 t of animal and poultry manure, and 5.8×10^8 t of agro-processing residues. These numbers indicate the high scale of agricultural waste production and the pressing need for sustainable waste management strategies. After China, India is considered the world's second-largest producer of agro-wastes, producing about 130 million tons of paddy straw, half of which is utilized for animal feed, while the other half is wasted. Furthermore, the practice of burning residue in the northwestern area produces significant air pollution and causes public health issues (Koul, Yakoob, and Shah, 2022).

Research has revealed valuable details on the types and quantities of agricultural waste. Taherzadeh *et al.* (2019) discussed the large amounts of solid waste produced from agricultural and forest fields, such as corncob, sugarcane bagasse, and rice husk. Jia *et al.* (2018) estimated the production of crop residues and livestock manure in China, with 819 Mt of crop residue and 551 Mt of manure produced in 2014. A great part of these organic materials might be composted. The study also shed light on the need for escalating the recycling of organic waste through composting, especially in areas with high manure burdens to meet sustainable and environmental goals.

Chávez-Fuentes *et al.* (2017) provide a comprehensive analysis of the environmental impact of agricultural animals, particularly in terms of manure production and methane potential. The study highlights the significant amount of manure produced by these animals, estimating it to be as much as 20 million tons of dry matter and 10 million tons of organic dry matter daily.

7.3.3 Agricultural waste impact on ecosystem and biodiversity concerns

7.3.3.1 Ecosystem impact

Habitat degradation: Agricultural waste contamination can modify the natural environment state by bringing in an overabundance of nutrients, chemicals, and organic matter into ecosystems. This alteration may result in habitat degradation and fragmentation (Gupta, Misra, and Ghosh, 2023), impacting the endurance and generative success of many species (Figure 7.1).

Altered nutrient dynamics: Extravagant nutrients from agricultural runoff, like nitrogen and phosphorus, can disrupt natural nutrient cycles in ecosystems. This interruption can result in nutrients being out of equilibrium, algal blooms, and oxygen runoff in water bodies, severely affecting aquatic life (Xia *et al.*, 2020).

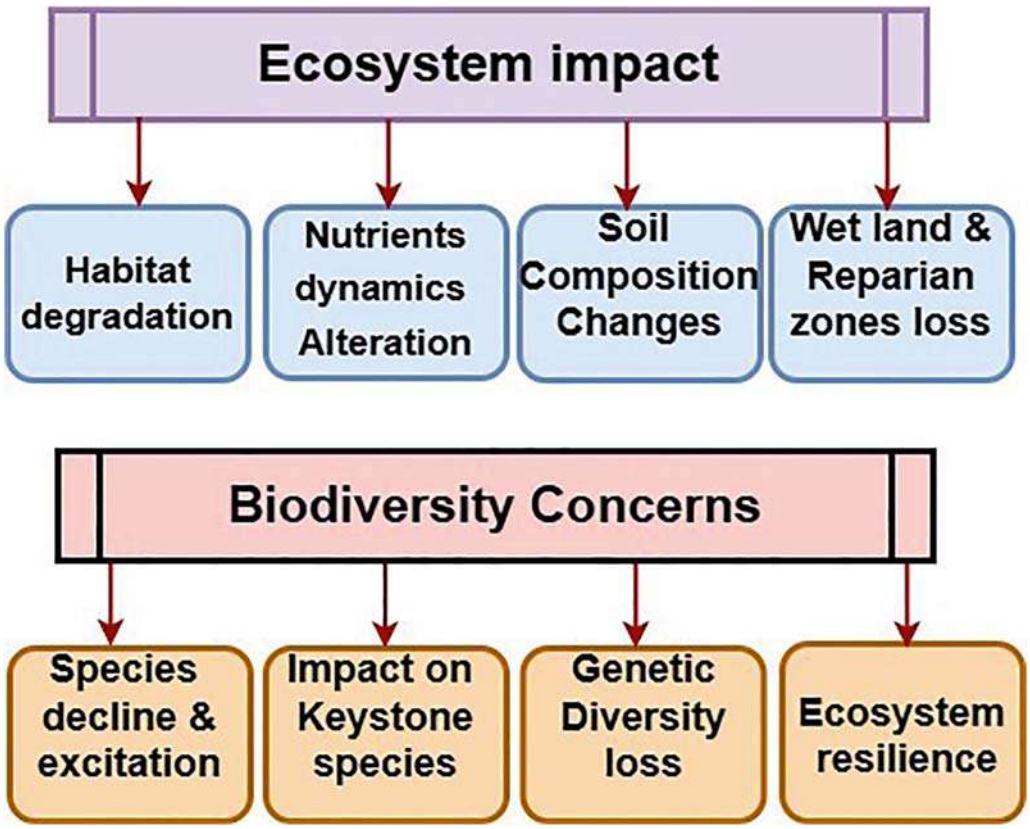


FIGURE 7.1 Flow chart on agricultural waste impact on ecosystem and biodiversity concerns. Illustrating the ecosystem impact and biodiversity concerns due to human activities.

Changes in soil composition: The discarding of agricultural residues can change soil composition and nutrient availability, impacting soil fertility and microbial populations. This change can cause soil erosion, compaction, and loss of soil biodiversity, further increasing ecosystem deterioration (Dingkuhn *et al.*, 2024).

Loss of wetland and riparian zones: Contamination from agriculture can deteriorate wetlands and riparian areas, which serve as critical habitats for many plant and animal species. Loss of these habitats can decrease biodiversity and damage ecosystem functions such as water filtration and flood control (Fang *et al.*, 2023).

7.3.3.2 Biodiversity concerns

Species decline and extinction: Contamination from agricultural residue may directly damage plants and animals by subjection to toxins or habitat ruin. This harm can result in community decreases and, in maximal cases, local extinctions of vulnerable species (Bélanger and Pilling, 2019).

Impacts on keystone species: Agricultural pollution may disturb the connections between species in ecosystems, especially those including keystone species. Keystone species play crucial roles in preserving ecosystem structure and function, and their decrease may have cascading impacts on the whole ecosystem (Gagic *et al.*, 2017).

Genetic diversity loss: Contamination-induced pressures such as chemical pollution and habitat degradation can diminish genetic diversity within populations, making species more vulnerable to diseases, environmental alterations, and other risks (Organization, 2024).

Ecosystem resilience: Decreased biodiversity caused by agricultural residue contamination can mitigate the persistence of ecosystems to disruptions like climate change, interfering species, and disease epidemics. This decrement in persistence can escalate the susceptibility of ecosystems to additional degradation and collapse (Isbell *et al.*, 2011).

7.3.4 Effects on soil and water quality

To address the issue of agricultural waste's impact on soil and water quality, it is critical to comprehend the numerous factors at play and the potential available solutions.

The nutrients involved in wastes such as nitrogen and phosphorus can run off into groundwater or run into rivers and lakes, affecting water quality. Also, the accumulation of waste makes crops more vulnerable to pests, diseases, and environmental change.

Researchers such as Sayara *et al.* (2020) have explored the effect of agricultural wastes on soil and water quality. They have water available for plants underscoring the positive impacts of organic waste recycling on water retention soil porosity and plant-available water. Soil organic matter is crucial for maintaining fertile and productive soil, with substantial influences on soil physical properties. By returning crop residues to the soil and implementing management practices such as no-till with residue return, soil organic matter levels can be increased, which in turn enhances soil physical characteristics and improves water infiltration and retention.

Studies have shown that adding organic matter to the soil through various activities enhances healthy crops, supports soil organisms, and regulates the main resources for plant production. It also promotes plant-available water, with a potential increase of up to 30%, which also supports other soil properties. Oliveira *et al.* (2018) found that organic wastes from various production series in the semi-arid region of Ceara hold the potential as organic fertilizers. Their nutrient contents can enhance soil fertility. Nevertheless, it is crucial to carefully consider the nutrient content of organic residues to prevent the negative impact on soil quality. For instance, shrimp farming may have negative effects on soil quality.

Open burning of crop residue, while easy and inexpensive (Ravindra *et al.*, 2019), releases various pollutants into the atmosphere, such as organic carbon, carbon monoxide, carbon dioxide, sulfur dioxide, NH_3, CH_4, and polycyclic aromatic hydrocarbons (PAHs). The disposal and distribution of pollutants vary according to the weather, season, and type of agricultural waste. These emissions have a substantial impact on atmospheric chemistry, radiation balance, and cloud microphysics, ultimately affecting the climate. Therefore, sustainable agricultural strategies and reasonable waste management are crucial to lower the environmental effects of agricultural activities and maintain soil and water quality for future generations.

While agricultural wastes might have negative environmental consequences, their wise management and proper recycling can result in improved soil and water quality. Therefore, it is important to convert agricultural waste into value-added products, highlighting the potential for green extraction techniques to recover metabolites from these wastes (Amran *et al.*, 2021).

7.4 Greenhouse gas emissions in agriculture: Sources and dynamics

7.4.1 Major contributions to agricultural greenhouse gas emissions

7.4.1.1 Livestock emissions

7.4.1.1.1 Enteric fermentation in ruminants Strategies to mitigate enteric methane emissions include improving feed quality and digestibility, using feed additives and supplements like seaweed, and modifying the rumen microbiome through microbial engineering (Sanjorjo *et al.*, 2023). However, these mitigation approaches must be carefully evaluated for their

impacts on animal productivity and nutrition. Supplementation with tropical tree foliage has shown potential in reducing methane production and altering the volatile fatty acids (VFA) profile (Alayón-Gamboa *et al.*, 2023). The use of exogenous enzymes in ruminant feed has been explored to enhance feed utilization and potentially reduce enteric CH_4 emissions per unit of product, while probiotic supplementation with *Enterococcus faecium* showed a reduction in methane concentrations with certain supplementation levels (Mamuad *et al.*, 2019). This methane is then released into the atmosphere, primarily through belching. Methanogenesis occurs when non-digested carbohydrates are fermented by contributing microorganisms in the rumina (methanogenic archaea), producing CH_4 (Roques *et al.*, 2024). Over 200 species of microorganisms, including bacteria, archaea, protozoa, and fungi, reside in the rumen and facilitate this fermentation process.

Enteric fermentation is a significant contributor to global greenhouse gas emissions, accounting for up to 30% of total methane emissions. Cattle are the primary emitters among ruminants, followed by other livestock like buffalo, sheep, and goats. Factors that affect the level of enteric methane production include animal species, age, feeding strategies, diet composition, and environmental conditions. Reducing these emissions is an important target for climate change mitigation in the livestock sector.

7.4.1.1.2 Manure management practices According to FAO, a huge amount of nitrogen from manure is deposited on agricultural soils, and this amount is volatilized in the atmosphere primarily as ammonia gas. Simultaneously, approximately nitrogen could be lost by leaching into soil water and runoff, which contaminated streams and water bodies. The entire global environmental impact in terms of excess N accounted for half of the total amount of manure put on agricultural land. Manure management, manure left on pastures, and manure applied to soils are the three categories under which GHG emissions from manure are categorized (Solomon, 2007). Manure management includes CH_4 and N_2O emissions, which originate from manure decomposition through aerobic and anaerobic processes. Moreover, the manure applied to soils includes N_2O emissions, which originate from soils due to manure applications. According to earlier reports, manure management is responsible for roughly 10% of the greenhouse gas emissions from livestock worldwide (5% from N_2O and 4% from CH_4) and 7% from agriculture. Table 7.1 shows the top 10 emitters of GHG emissions

TABLE 7.1 Top 10 emitters of GHG emissions through livestock total, enteric fermentation, manure management, and manure left on pasture (Average 1961 − 2021).

Year	Livestock total (emissions N_2O)	Livestock total (emissions CH_4)	Enteric fermentation (emissions CH_4)	Manure management (direct emissions N_2O)	Manure left on pasture (direct emissions N_2O)
China, Mainland	341.05	7067.44	6196.85	85.94	128.38
USSR	283.56	10467.6	9233.66	51.05	68.26
Brazil	272.66	8987.66	8777.19	10.77	189.63
United States of America	229.75	7949	6594.73	35.87	113.47
India	221.21	12455.96	11482.56	9.31	134.78
Australia	117.99	2761.52	2584.6	-	83.58
Argentina	95.18	3249.61	3182.78	-	72.63
Ethiopia	93.36	-	-	-	72.47
Sudan	82.03	-	-	-	61.78
Mexico	71.12	1972.28	1904.56	-	46.16
Russian Federation	-	2604.22	2257.39	13.48	-
Pakistan	-	2459.97	2277.61		-
Indonesia	-	-	-	9.34	-
France	-	-	-	9.15	-
Germany	-	-	-	8.28	-
Myanmar	-	-	-	6.88	-

Adapted from FAOSTAT, 2023. FAOSTAT database. https://www.fao.org/faostat/en/#data/GLE/visualize. (Accessed 13 May 2024).

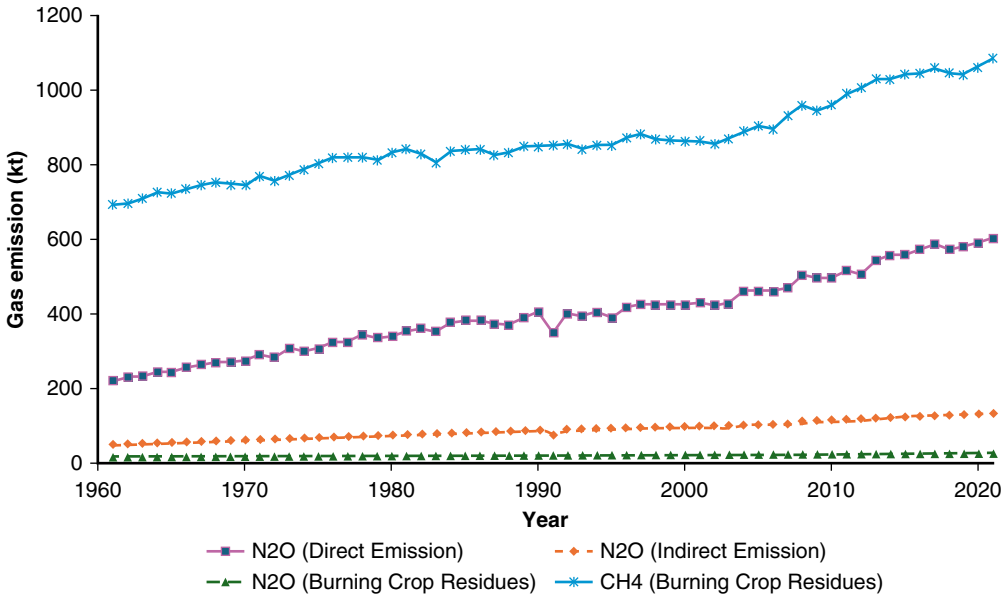


FIGURE 7.2 Annual increase in greenhouse gas emissions over 1960 to 2020. Annual trend of greenhouse gas (GHG) emissions, illustrating a consistent increase over the years. *Adapted from FAOSTAT, 2023. FAOSTAT database. https://www.fao.org/faostat/en/#data/GLE/visualize. (accessed 13.05.24).*

through livestock total, enteric fermentation, manure management, and manure left on pasture. Cattle account for most manure management emissions, with systems based on liquid manure having the greatest emissions rate. Emissions are the largest in Asia and Europe. Figure 2 shows that GHG emissions rise annually.

The reduction of crude protein levels in the feeding formulation has shown a significant impact on the proportions of nitrogen in feces and urine, which is the main source of NH_3 and N_2O generation (Yan *et al.*, 2024). A modern approach in manure management is the employment of anaerobic digestion technology. Anaerobic microorganisms ferment animal manure in the absence of oxygen, resulting in a reduction in the overall methane emission and providing an alternative source substituting fossil energy. The captured methane can be used for bioenergy production while reducing up to 4 kg per capita of CO_2-eq of annual carbon emission (Mundra and Lockley, 2024) (Figure 7.2).

7.4.1.2 Soil emissions

7.4.1.2.1 Nitrous oxide from agricultural soils Nitrous oxide (N_2O) has a significant GHG footprint with a substantial contribution to both global warming and the stratospheric ozone layer depletion. According to US EPA, 2024, the global warming potential of N_2O is 273 times that of CO_2 for a 100-year timescale with an average residence time over 100 years. Higher than 70% of the total N_2O emissions arise from agricultural lands and emanate from microbial-based nitrification and denitrification activities. Agriculture participates in the emission of N_2O due to (1) escalating agricultural and other anthropogenic activities, (2) expansion of synthetic nitrogen fertilizers use globally, (3) cumulation of animal residue (urine and dung) from foraging animals, (4) extravagant and ineffectual use of farm discharge and animal manure on croplands and grazing, (5) stewardship strategies that enhance soil organic matter mineralization, carbon decomposition, and carbon dioxide emission (Velthof and Rietra, 2018). In addition, the FAOSTAT domain crops residues' emissions, crop residues' burning, and applying mineral and chemical fertilizers nitrogen (N) to soils. Approximations are calculated at Tier 1 following the 2006 IPCC Guidelines for National GHG Inventories (Solomon, 2007). Menegat, Ledo, and Tirado's study (2022), which explored GHD emissions from the generation and usage of nitrogen synthetic fertilizers globally, found that synthetic fertilizers were computed to be responsible for 10.6% of agricultural emissions and 2.1% of world GHG emissions. Of all emissions relevant to synthetic N fertilizers, 38.8% came from the production of synthetic N fertilizers, 58.6% came from field emissions, and the remaining 2.6% came from transportation. Sixty-two percent came from the top four contaminators: China, India, the United States, and the European Union. Reducing the total amount of synthetic N fertilizer produced and used offers significant mitigation potential for GHG emissions. Strategies to mitigate N_2O emissions include optimizing soil and climatic conditions, type of fertilization, nitrification inhibitors, and diversified crop rotation (Bianchi *et al.*, 2021). Different plowing and cultivation practices were found to impact soil carbon distribution and soil microbiota activity, resulting in varied N_2O emissions (Poblador, 2022).

7.4.1.2.2 Carbon dioxide from soil management Carbon dioxide (CO_2) interferes with the atmosphere by the burning of fossil fuels (natural gas, coal, oil), trees, solid waste, and other biological substances and is removed from the atmosphere (or "concealed") when plants absorb it during the biological carbon cycle. The majority of CO_2 emissions from agriculture are ascribed to plant waste that has been integrated into soil (Chataut *et al.*, 2023). Soil management procedures such as land reclamation, the use of chemical and organic fertilizers, and the application of green manures influence CO_2 emissions from agricultural soils (Polioviy, 2024). Li *et al.* (2023) investigated the impact of irrigation practices by testing recycled water, at different levels for soil irrigation, on CO_2 emission and reported a 58.1% increase in CO_2 emission compared to freshwater irrigation. Agricultural management and fertility practices such as diverse cropping, no-till farming, minimum tillage, and minimum machinery operations are recommended to reduce the agriculture-based carbon footprint (Ozlu *et al.*, 2022). Land management practices can control GHG emissions by increasing organic matter content and stimulating microbial diversity. Moreover, Polioviy (2024) showed that lime application in short-term crop rotation had a positive effect on the balance of organic carbon in sod-podzolic soil and decreased CO_2 emissions.

7.4.1.2.3 Quantifying emissions from different farming practices Farm practices are responsible for 25 to 30% of global GHG emissions, with the scale varying based on the agricultural model and the level of economic development (Czyżewski and Kryszak, 2018). Emission alterations can be assessed by biogeochemical modeling to address possible concerns. The development of tools for GHG quantification in smallholder conditions, as well as the whole farm scale, reveals the variability in emissions between different farm typologies and the importance of adopting improved practices (Seebauer, 2014).

CH_4 and N_2O emissions could have originated from crop residues burned in the field, as indicated by the FAOSTAT (Table 7.2). Figure 7.3 shows that GHG emissions rise annually. Emissions of N_2O from crop residues and burning crop residues are dominated by rice, followed by wheat and maize (Table 7.2). Meanwhile, emissions of CH_4 from burning crop residues are dominated by maize, followed by rice and wheat. Emissions of N_2O and CH_4 are largest in Asia (mainly China) and followed by America. Because of its extensive rural population and intense agricultural practices, China is the world's greatest producer of agricultural waste (McClelland *et al.*, 2023). The inefficiencies in the methods used for managing, disposing of, and using agricultural waste result in more than half of it being wasted and released into the environment.

TABLE 7.2 The latest emission data from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT).
Ten top emitters of GHG emission through crop residues and burning crop residues (Average 1961 – 2021)

	Direct N_2O emission from crop residues	Indirect N_2O emission from crop residues	N_2O emission from burning crop residues	CH_4 emission from burning crop residues
China, Mainland	68.25	15.36	3.69	142.14
United States of America	59.1	13.3	2.67	102.81
India	47.59	10.71	2.87	110.89
USSR	39.18	8.81	1.95	75.19
Russian Federation	19.57	4.4	0.78	30.03
Brazil	16.45	3.7	1.29	49.8
Argentina	9.64	2.17	-	-
Indonesia	9.52	2.14	0.63	24.25
France	9.27	2.09	-	-
Canada	9.26	-	-	-
Ukrainea	-	2.08	-	-
Mexico	-	-	0.55	21.36
Thailand	-	-	0.47	17.99
Bangladesh	-	-	0.42	16.32

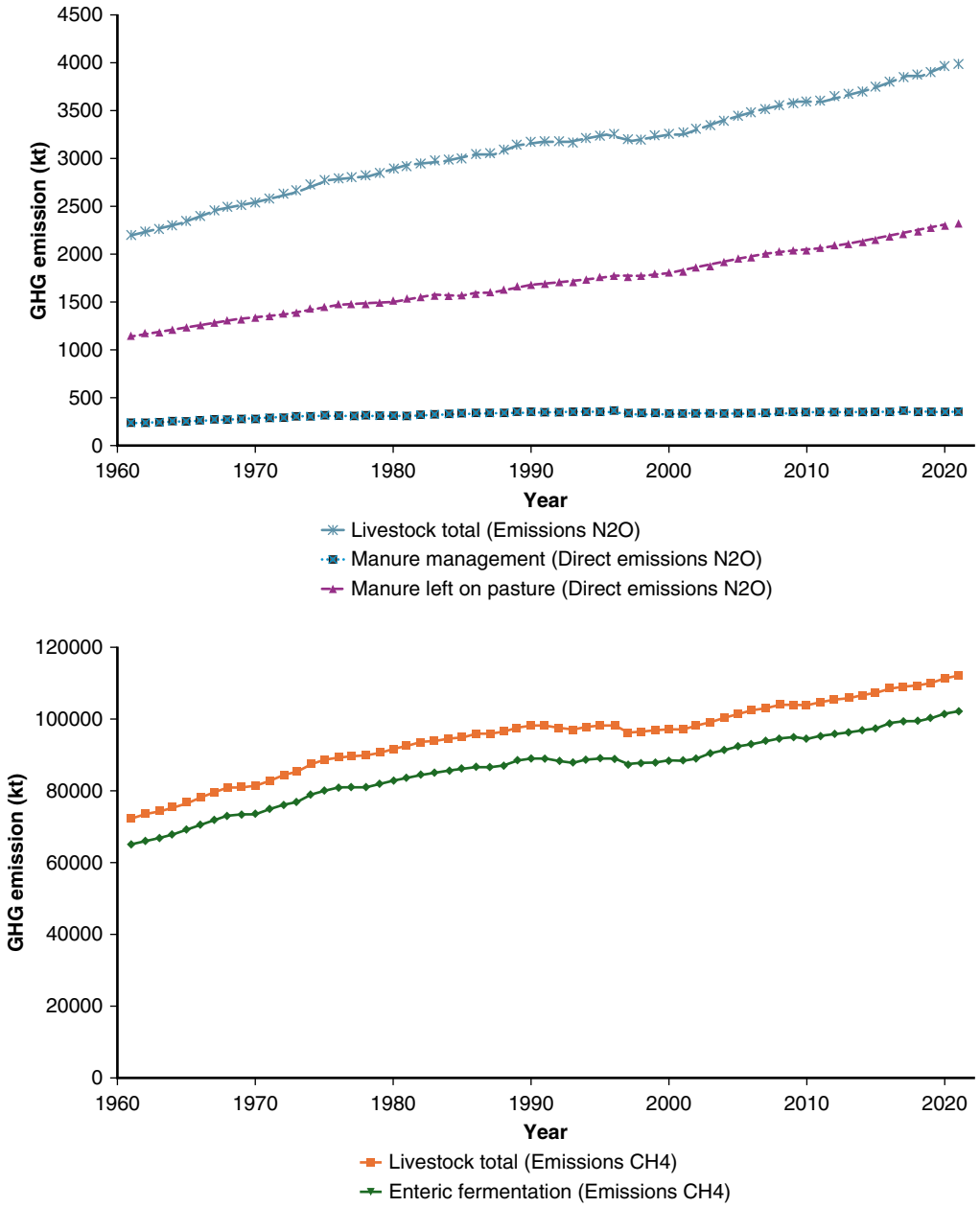


FIGURE 7.3 Annually GHG (N_2O and CH_4) from burning crop residues (the latest emission data from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT). Annual greenhouse gas emissions N_2O and CH_4 from burning crop residues (average 1961−2021). *Adapted from FAOSTAT, 2023. FAOSTAT database. https://www.fao.org/faostat/en/#data/GLE/visualize (accessed 13.05.24).*

7.4.1.2.4 Understanding the role of livestock, soil, and energy use

Livestock production contributes significantly to the levels of GHGs both directly, through CH_4 emission, and indirectly, through N_2O emission. Activities including fertilizer applications, tillage, and irrigation are important factors to determine the level of contribution from the agricultural fields to GHGs. Practices such as tillage can impair the soil structure by oxidizing carbon and causing GHG emissions, while no-till or minimum tillage is recommended to reduce that effect (Ozlu *et al.*, 2022). In addition, the carbon footprint is affected by energy usage in agriculture such as the excessive application of mineral fertilizers and fossil fuels resulting in higher levels of N_2O and CO_2 (De Rosa *et al.*, 2018). Integrated systems that combine crops, livestock, and forests have been shown to improve soil quality and biological characteristics, mitigate GHG emissions, and present negative methane fluxes. Thorough mitigation approaches are needed to enhance agricultural efficiency at the levels of livestock, soil management, and energy use, with precision farming and integrated systems offering promising solutions (Nair and Mukherjee, 2022).

CH_4 and N_2O emissions could have originated from crop residues burned in the field, as indicated by the FAOSTAT (Tables 7.2 and 7.3). Figure 7.3 shows that GHG emissions rise annually. Emissions of N_2O from crop residues and

TABLE 7.3 **The latest emission data from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT).**
Emission of N_2O and CH_4 from crop residues and burning crop residues by crops (on average 1961 – 2021)

	Direct N_2O emission from crop residues	Indirect N_2O emission from crop residues	N_2O emission from burning crop residues	CH_4 emission from burning crop residues
Barley	29.09	6.54	-	-
Beans, dry	4.54	1.02	-	-
Maize (corn)	76.36	17.18	9.84	379.62
Millet	5.48	1.23	-	-
Oats	6.98	1.57	-	-
Potatoes	11.09	2.5	-	-
Rice	105.71	23.78	5.63	-
Rye	4.67	1.05	-	217.21
Sorghum	13.84	3.11	-	-
Soya beans	32.34	7.28	-	-
Wheat	108.89	24.5	6.17	238.16
Sugarcane	-	-	0.8	30.83

TABLE 7.4 **The latest emission data from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT).**
Emission of N_2O and CH_4 from crop residues and burning crop residues by continent (on average 1961 – 2021)

	Direct N_2O emission from crop residues	Indirect N_2O emission from crop residues	N_2O emission from burning crop residues	CH_4 emission from burning crop residues
Africa	24.16	5.44	2.34	90.3
America	104.52	23.52	5.85	225.74
Asia	181.27	40.79	10.81	416.95
Europe	83.38	18.76	3.13	120.56
Oceania	5.66	1.27	0.32	12.27

burning crop residues are dominated by rice, followed by wheat and maize (Table 7.4). Meanwhile, emissions of CH_4 from burning crop residues are dominated by maize, followed by rice and wheat. Emissions of N_2O and CH_4 are largest in Asia (mainly China) and followed by America. Because of its extensive rural population and intense agricultural practices, China is the world's greatest producer of agricultural waste (Koul, Yakoob, and Shah, 2022). The inefficiencies in the methods used for managing, disposing of, and using agricultural waste result in more than half of it being wasted and released into the environment.

7.5 Methodologies for ecological footprint calculation

7.5.1 Life cycle assessment (LCA) in agriculture

Life cycle assessment (LCA) was initiated as a required tool for quantitative evaluation of the environmental impacts of the complete life cycle of an agricultural product or process from resource acquisition and production to disposal and recycling (Usman Sajid et al., 2023). Adapting the LCA methodological framework has been used to assist in the identification of environmental flashpoints and possible sustainability improvements through four main components: (1) goal definition and scoping, (2) life cycle inventory analysis, (3) environmental impact assessment, and (4) interpretation.

Recent improvements in LCA include the integration of LCA with Geographic Information System (GIS) to address spatial environmental impacts of farming practices on a larger scale (Mealing and Landis, 2023). Sajid *et al.* (2023) conducted LCA to compare conventional and spectra-managed greenhouses purposely used in hot and arid climates. Spectra-managed greenhouses significantly reduce global warming potential by reducing cooling loads and environmental emissions, highlighting the promising innovation in using photovoltaics and nanofluids for sustainable cooling. In addition, LCA has been recently used to predict agricultural impacts in the production system to guide agricultural policymakers to make only environmentally friendly decisions (Moghaddam, Moghaddam, and Esfandyari, 2016). The engagement of digitalization and big data utilization in LCA practices has been recognized as a powerful approach, specifically with the large available agricultural data, to improve the accuracy of LCA outcomes. Moreover, LCA has been used as a tool that advocates more sustainable agriculture practices by being embedded in eco-labels and sustainability certifications (Li *et al.*, 2023).

7.5.2 Carbon footprint measurement

Carbon footprint in agriculture is an essential avenue for the valuation of the ecological effects of the agri-food system. It integrates the total GHG emissions, expressed as carbon dioxide equivalents (CO_2eq), released directly or indirectly by all agricultural activities. It is deliberated tier-wise, including direct on-site emissions "Tier 1," indirect farm emissions "Tier 2," and indirect emissions from manufacturing and transport "Tier 3" (Jaiswal and Agrawal, 2020). Diverse methodologies have been established to account for carbon footprints, such as life cycle analysis, farm gate methods, and approaches based on data collection and secondary statistics. Corporations and governments aim to establish environmental sustainability through the integration of carbon reduction strategies into business models and supply chain efforts (Koushika *et al.*, 2024). Methods of carbon footprint measurement include life cycle assessment (LCA) and Input-Output Analysis (IOA). IOA includes two models, the Single-Regional Input-Output (SRIO) and the Multi-Regional Input-Output (MRIO) (Miao *et al.*, 2023). SRIO is the traditional model suitable for the assessment of the total consumption of a region by using the input-output table to evaluate the environmental impact of final demand. The limitation of this model includes the omission of the impact of technological variation in different territories on carbon footprint (Han *et al.*, 2022). For example, the SRIO model cannot manifest the GHG emissions from imported products that are consumed in different regions (Fang, 2015). On the other hand, the MRIO model was established to adapt trade globalization in the comprehensive estimation of environmental loads in a larger scope through the connection of multiple sectors in multiple regions (Miao *et al.*, 2023). It includes the input and output structure and represents carbon and pollutant emissions of diverse countries. Moreover, the IOA method was modified to demonstrate the associations between agricultural production, consumption, and hidden environmental costs (Miao *et al.*, 2023).

7.5.3 Incorporating biodiversity considerations

Human agricultural activities have caused severe deterioration to environmental biodiversity, either directly or indirectly. Land use has been recognized as the biggest threat to biodiversity. Recent research demonstrates the necessity for incorporating biodiversity impacts into the Environmental Impact Assessment (EIA) index system of agriculture (Fan *et al.*, 2022). By integrating biodiversity consideration into LCA, possible impacts of farm practices on biodiversity will be predicted and avoided (Loustau, Lefer, and Ducos, 2024). Procedures for considering biodiversity in LCA have been developed, focusing on the abundance, richness, and evenness of organisms and species composition. Lindner *et al.* (2019) proposed a new LCA framework method that estimates the influence of land-using practices on biodiversity and is adapted to account for regional conservation priorities. McClelland *et al.* (2023) incorporated biodiversity in livestock system analyses using two approaches toward quantifying biodiversity influences: (1) pressure-state-response and (2) potential species loss. They recommended complementary application of the two approaches to obtain both absolute and per-unit product biodiversity impacts. Jeanneret *et al.* (2014) established an expert scoring system that incorporates organismal diversity as an LCA impact category in agriculture without the requirement to specify initial biodiversity status. The prediction of possible impacts on biodiversity is estimated through 11 indicator-species groups (flora of crops and grasslands, birds, mammals, amphibians, snails, spiders, carabids, butterflies, wild bees, and grasshoppers).

7.6 Technological innovations in shaping ecological footprint reduction

7.6.1 Role of innovation in sustainable agriculture

Innovation efficiency indicates the effective allocation and utilization of scientific and technological resources over space and time, reflecting regional capabilities for technological innovation (Hauge *et al.*, 2018). The ecological footprint, which

gauges human impact on the environment, serves as a comprehensive indicator of ecological quality. Therefore, it is crucial to assess the influence of innovation efficiency on the ecological footprint, understand their relationship, and consider the effects of regional economic development on this dynamic. While numerous studies have explored various factors affecting the ecological footprint (Solís-Guzmán, Marrero, and Ramírez-de-Arellano, 2013), few have delved into these impacts from the perspective of innovation efficiency. Additionally, given that the ecological footprint extends beyond local issues, China's per capita ecological footprint shows significant spatial clustering rather than randomness (Zambrano-Monserrate *et al.*, 2020).

Research on the relationship between technological innovation and the ecological environment is primarily approached from three perspectives. First, technological innovation can improve the ecological environment. According to the Porter hypothesis, encouraging the "innovation compensation" effect through technological innovation is a key strategy for reducing pollution emissions (Leach *et al.*, 2012). The IPAT model (Impact = Population × Affluence × Technology) links environmental impact with population size, per capita wealth, and technological level, suggesting that technological advancements can alleviate the environmental pollution caused by population growth (Ehrlich and Holdren, 1971). Second, not all technological innovations enhance the ecological environment. In regions with advanced industrial development, increased technological innovation can lead to higher levels of environmental pollution. Studies have shown that technological innovation can negatively impact the environment, particularly during the early stages of industrial agglomeration when there is insufficient motivation for clean production technologies (Fan, Cao, and Ma, 2020; Fan *et al.*, 2022). In such cases, the focus is often on improving product technology to increase profits, neglecting environmental protection. Additionally, in the early stages of industrial agglomeration, inadequate infrastructure and public pollution control facilities can hinder efforts to reduce marginal pollution control costs (Wang *et al.*, 2021). The third perspective suggests that the impact of technological innovation on the ecological environment follows an inverse U-shaped relationship. Technological innovation and progress may initially harm the environment but can curb carbon emissions in the long term (Verhoef and Nijkamp, 2002). This implies a nonlinear relationship where initial environmental degradation is followed by subsequent improvement, indicating that the impact of innovation efficiency on the ecological footprint may also follow this pattern, characterized by initial inhibition and later promotion. Overall, improving innovation efficiency may influence the ecological footprint through four main channels: population aggregation, industrial structure, energy structure, and energy efficiency.

7.6.2 Gaps and opportunities for improvement

Despite many studies conducted in the field of EF, many gaps can be summarized based on the study of Kazemzadeh *et al.* (2023).

Previous studies have primarily focused on investigating the correlation between organizational quality and CO_2 emissions. However, uncovering the association between institutional quality and environmental footprint should be done.

The relationship between fragile state and ecological footprint has not been studied extensively previously; therefore, applying new and further dimension to the research is needed.

Previous studies typically used conventional econometric methods and studied each factor's influence on environmental quality; thus, considering the complex solutions that result from the combination of factors affecting the ecological footprint will be beneficial to improving the study's accuracy and comprehensiveness. Therefore, it is crucial to acknowledge the gaps and highlight the need for future studies to incorporate a more diverse sample to ensure the findings are generalizable.

The solutions presented by a certain study for reducing the ecological footprint may rely on certain models that may not be valid in all cases.

Using additional or new models to improve the conclusions and presenting more inclusive solutions for decreasing the EF is recommended to address these limitations.

7.7 Challenges and future considerations

7.7.1 Barriers to effective ecological footprint reduction

7.7.1.1 Lack of awareness

Many farmers, food producers, and consumers are unaware of the environmental impacts of agricultural waste, including its involvement in pollution and greenhouse gas emissions. Without a thorough awareness of these concerns, it is difficult to persuade individuals and organizations to take action to lessen their ecological imprint. Further, some of the barriers in this category include a lack of consumer interest in green products, a lack of knowledge about green products, and an inability to get market resources to develop green products (Gupta and Barua, 2018).

7.7.1.2 Financial constraint

Another barrier to successful ecological footprint trimming is the lack of incentives and support for sustainable strategies in agriculture. Many farmers and food producers encounter financial restrictions that make it hard for them to put money into ecologically safe operations and applications. Without sufficient financial support, it can be challenging for these stakeholders to make major changes to minimize their ecological footprint (Adisa, 2024).

7.7.1.3 Regulatory policies

Regulatory barriers can also obstruct attempts to lower the ecological footprint of agricultural residue. Under certain conditions, regulations may not be strict enough to encourage sustainable practices, or they may be too oppressive for farmers and food producers to adhere to (Shukla, 2019). To efficaciously diminish pollution and greenhouse gas emissions from agricultural waste, it is vital to advance and carry through blueprints that strike a balance between environmental safeness and economic viability.

7.7.2 Anticipating future challenges in agricultural waste and emission management

- **Policy and regulatory landscape:** Efficient waste and emission administration demands obvious and consistent policies and rules. Nevertheless, evolving and applying such frameworks can be exacting, particularly in a globalized agricultural system with diverse policing and imposition appliances. Legislators should actively work with concerned parties, including farmers, industry agents, environmental NGOs, and scientific authorities, to ensure those policies are applied, practical, and socially acceptable. Coactive decision-making operations can improve transparency, build trust, and strengthen adherence to ecological regulations (Sinha *et al.*, 2022).
- **Growing stepping up and reinforcement:** The world population is estimated to reach 9.7 billion by 2050 (Tripathi *et al.*, 2018), demanding a marked increase in production of foodstuffs. This pressure will probably drive agricultural build-up, leading to growing yields and potentially higher waste production. Addressing this rush of waste, particularly in developing countries with limited infrastructure, will be critical. Various inventions are now in development to meet the escalating population, and declining wages, while also promoting human health. Genetically modified crops are likely to grow faster than domestic varieties. Additionally, they can help alleviate famine and poverty by increasing the income of poor farmers. According to Aslam and Gul's (2020) reports, genetically modified organisms (GMOs) minimize greenhouse gas emissions and pesticide use. Kumar and Sharma (2023) highlighted the importance of genetic engineering approaches, which are significant for designing transgenic microorganisms and plants to enrich biodetoxification and biodegradation of environmental pollutants for long-lasting development. GMOs also provide great possibilities for environmental remediation.
- **Climate change effects:** Climate change is so far having an impact on agricultural activities (Praveen and Sharma, 2019), resulting in more severe weather episodes, adjusted growing seasons, and escalated pest and disease expansion. These alterations can intensify waste generation and entangle emission handling. For example, droughts can cause crop failure and subsequently increase food waste since harvested crops are lost or rendered unsuitable for consumption. Livestock deaths are also caused by severe heat and droughts, generating significant organic waste. When farmers confront extreme weather events, they may need to adapt by changing crop kinds or agricultural operations, resulting in changes in waste streams as underused or surplus inputs are produced. Degraded soils caused by rising climate change are less productive and may require greater inputs such as fertilizers and soil amendments, resulting in higher waste from packaging materials, unused inputs, and nutrient runoff.
- **Technological improvements and new strategies:** While high-tech industries propound viable solutions, they also pose challenges. Precision agriculture (PA), for example, while boosting efficiency along with minimizing waste by targeting inputs such as water and fertilizers, may simultaneously generate new types of waste through several mechanisms. One example is plastic from sensors and drones (Rejeb *et al.*, 2022). Another example is that in a cloud-based system, a significant amount of energy is consumed to gather, store, and process data. If this energy is derived from nonrenewable sources, it may contribute to carbon emissions (Jayalath *et al.*, 2019). Overapplication of inputs, obsolete inputs, and infrastructure waste are likely pollutants produced by PA if management is not accurate. Similarly, genetically engineered crops, while potentially enhancing yields, may necessitate novel waste management solutions. Farmers, technology suppliers, legislators, and researchers must prioritize sustainable implementations (Bansod *et al.*, 2017), including appropriate disposal and reusing of technology elements, methodical data management strategies, precise calibration and maintenance of precision agriculture equipment, and continuous technology enhancement.

- **Changing consumer patterns:** It normally takes a long time for shifts in consumer behavior (Sharma, Nguyen, and Grote, 2018). Growing apprehension of environmental and ethical issues is leading to consumer dictate for sustainable agricultural implementations. This push will require a move concerning more responsible waste and emission management, possibly increasing costs and necessary novel strategies. Popp, Lotze-Campen, and Bodirsky (2010) developed a model to estimate future human agricultural non-CO_2 GHG emissions from diverse farming processes. Global agricultural non-CO_2 emissions will increase significantly until 2055, assuming food energy consumption and diet preferences remain unchanged at 1995 levels. Non-CO_2 GHG emissions will increase much more if income rises and people shift their dietary preferences to higher-value goods. For instance, compared to traditional animal-based proteins, protein-based sources derived from plants offer significant potential as sustainable alternatives due to their lower carbon footprint. Plant-based proteins help to minimize methane emissions and require less land and water. Nevertheless, many consumers believe that animal-based proteins are better in terms of protein quality and vital nutrients. This view, combined with the economic accessibility of animal-based proteins—often subsidized and supported by established supply networks—strengthens their widespread consumption. Further, the meat and dairy industries benefit from vast marketing and distribution chains that further reinforce consumer dependence on animal-based products. Social and cultural habits also play a substantial role, often making it challenging for individuals to shift toward plant-based diets. It is, therefore, necessary to develop and enhance plant-based protein products (Hamed *et al.*, 2024) that more closely resemble the taste, texture, and nutritional makeup of animal-based proteins to help encourage this transition. However, technological mitigation methods are less successful than reductions in food consumption. A combination of the two procedures will yield the highest reduction potential.
- **Resource scarcity:** Natural resource shortage is becoming a serious concern in many places of the world (Sun and Wang, 2023). Global food supplies are already threatened by soil degradation, water scarcity, and climate change, while biodiversity loss puts entire habitats and species at risk (Wassie, 2020). Natural resource scarcity is intimately related to agriculture, forestry, fisheries, fossil fuel energy usage, and overall greenhouse gas emissions. Countries with high emissions from these sectors frequently face increased resource shortages. Addressing the dynamics of value addition in these sectors, particularly in the highest-emitting countries, can promote sustainable development, reduce climate change, and assure the long-term viability of agricultural systems. Strategic policy interventions, as well as technology transfer, capacity building, and market-based mechanisms, can contribute to a more sustainable future while addressing the constraints of natural resource scarcity (Wang and Azam, 2024).

7.7.3 Gaps and opportunities for further research in shaping ecological footprint reduction

7.7.3.1 Quantification and characterization of waste streams

- **Gaps:** Present methodologies for evaluating and characterizing agricultural residue cascade may need accuracy and uniformity, resulting in miscalculation and misrepresentation of their environmental imprint.
- **Opportunities:** Research pivoting on upgrading data-gathering methods, standardizing estimation methodologies, and including life cycle measurements can improve our comprehension of the constitution, dispersal, and ecological impacts of agricultural residue.

7.7.3.2 Technological innovations for waste management

- **Gaps:** Although diverse waste-handling machinery exists, its assumption in agricultural surroundings may be obstructed by components like price, expandability, and harmony with farming activities.
- **Opportunities:** Research into inventive waste-handling technologies, such as anaerobic decomposition, composting, and producing biochar, can provide sustainable alternatives for transforming agricultural residue into of-value resources while decreasing ecological pollution and greenhouse gas emissions.

7.7.3.3 Integrated farming systems and circular economy approaches

- **Gaps:** The shift to more sustainable agriculture systems needs comprehensive avenues that evaluate the linkages between farming outcomes, waste control, and ecosystem health.
- **Opportunities:** Exploring coherent agricultural systems that advance resource usage, lessen waste production, and encourage circular economy fundamentals can provide approaches for minimizing the ecosystem footprint of agriculture. This comprises investigating agroecological activities, crop-livestock incorporation, and harmonious connection between agriculture and other sectors.

7.7.3.4 Policy and governance mechanisms

- **Gaps:** Despite the significance of strategies and political frameworks in forming agricultural waste control practices, there may be contradictions, gaps, or lack of enforcement in the existing regulations.
- **Opportunities:** (Menegat, Ledo, and Tirado, 2022) Research concentrating on the efficacy of policy implementation, governmental settlement, and governance appliances can inform the design and execution of policies that foster sustainable practices, encourage innovation, and boost the fulfillment of ecological standards.

7.7.4 Successful eco-friendly models

Many countries such as Australia (Panchasara, Samrat, and Islam, 2021) and the United States (McNunn *et al.*, 2020) have followed the IPCC guidelines to multiply agricultural production while minimizing waste pollution and GHG emissions. One of the important case studies worldwide is China. It is the highest contributor to GHG emissions. China pledged a commitment to the world in 2020 prioritizing mitigating carbon emissions by 2030 and reaching carbon neutrality by 2060. The empirical literature has shown several examples to mitigate GHG and improve productivity in China regions. The dataset of 31 provinces in China from 2000 to 2019 has suggested that prompting green agricultural development through applying zero-tillage planting and straw returning significantly inhibited the carbon footprint (Guo and Zhang, 2023). In recent research, a meta-analysis of 2,221 observations concerning GHG in seven agro-ecological zones in China concluded that region-specific management strategies, including fertilizer applications, straw management, irrigation, and tillage system, precisely optimized to fit each agro-ecological region (Li *et al.*, 2024).

7.8 Conclusion and recommendations

Agriculture still plays a crucial role in the world's food production, but it also significantly contributes to environmental challenges, particularly through waste generation and greenhouse gas emissions. This chapter has underscored a number of critical aspects regarding the impact of agricultural activities that affect the environment, with an emphasis on waste management, ecosystem impacts, and greenhouse gas emissions. In the tracking of alleviating the ecological footprint of agriculture and establishing the sustainability of our food systems, it is vitally important to execute holistic strategies that address waste control, develop sustainable agricultural practices, promote innovation, validate supportive policies, build up education and awareness, and open the door for international collaboration. As the agricultural sector copes with challenges related to resource depletion, environmental degradation, and climate change, these recommendations provide a comprehensive approach to not only minimize ecological pollution but also boost resilience and productivity.

Governments and agricultural stakeholders should prioritize investments in sustainable waste management infrastructure, like composting, anaerobic digestion, and biochar generation. This will help turn agricultural residue into cherished resources while minimizing ecological contamination and greenhouse gas emissions. Promoting the appropriation of sustainable farming capabilities such as crop rotation, minimum tillage, and precision agriculture may improve the health of soil, decrease waste production, and reduce greenhouse gas emissions. Incentives for organic farming, farmer education courses on sustainable techniques, and support for studies intended for developing crop types resistant to climate change are further measures taken to encourage sustainable practices.

The focus of research and development should be on cutting-edge waste management solutions designed specifically for agricultural environments. Governments and academic institutions ought to support agricultural innovation and efficiency. Promoting innovations that lower waste, increase energy efficiency, and lessen greenhouse gas emissions is part of this. This includes exploring new waste management solutions, developing climate-resilient crop varieties, and upgrading nutrient control practices. Governments should validate and impose policies that develop sustainable agricultural practices, motivate waste limiting and recycling, and modulate greenhouse gas emissions from agricultural activities. Synergetic efforts between legislators, farmers, industry collaborators, and environmental organizations are crucial for the efficient application of such policies. This chapter has investigated several dimensions of how innovation efficacy impacts the ecological footprint, ranging from its effect on population density and industrial structure to energy efficacy and consumption patterns. Insights from the literature highlight a complex relationship where technical advancements can both exacerbate and lessen ecological effects, underscoring the necessity of strategic innovation policies that support sustainable solutions. It is critical to put in place robust tracking systems to keep tabs on waste production and emissions from agriculture. With the help of this data, policy decisions can be made and allow targeted interventions to lessen environmental effects. Accelerating awareness among farmers, food producers, and consumers about the ecological effects of farming waste and emissions is essential. Education programs and awareness campaigns can strengthen stakeholders to endorse sustainable practices and make informed selections that contribute to reducing the ecological footprint of

agriculture. Given the global nature of agricultural residue and emissions, international contribution is crucial for discussing these challenges effectively. Sharing best practices, knowledge, and resources can ease the enhancement and implementation of holistic solutions that exceed geographical boundaries. Special attention should be given to vulnerable areas, including fragile states and places with inadequate resources or infrastructure. Customized research and policy initiatives can help these regions adopt sustainable agricultural practices efficiently. Future studies ought to use integrated frameworks that take into account how many factors that affect ecological footprints are interrelated. To create comprehensive answers, this calls for interdisciplinary research integrating agronomy, economics, environmental science, and policy analysis to evolve holistic solutions. By admitting the coordination of agricultural activities with environmental health and human well-being, these recommendations confirm the need for dynamic and joint endeavors across various collaborators. From farmers and legislators to researchers and consumers, each plays an essential role in adjustment toward a more sustainable and regenerative agricultural system.

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Chapter 8

Emissions from fertile to fragile: Understanding soil degradation and erosion due to agricultural waste

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Chapter Outline

8.1. Introduction 121
8.2. Impact of agricultural activities on soil health 123
8.3. Significance of addressing agricultural waste in soil conservation 123
8.4. Impact of agricultural waste on soil health 124
8.5. Strategies for managing agricultural waste 124
8.6. Understanding agriculture waste as a resource 125
8.7. Environmental impact of agricultural waste accumulation 126
8.8. Strategies for mitigating agricultural waste and soil degradation 128
8.9. Emerging trends in agricultural waste management 130
8.10. Conclusion 131
References 131

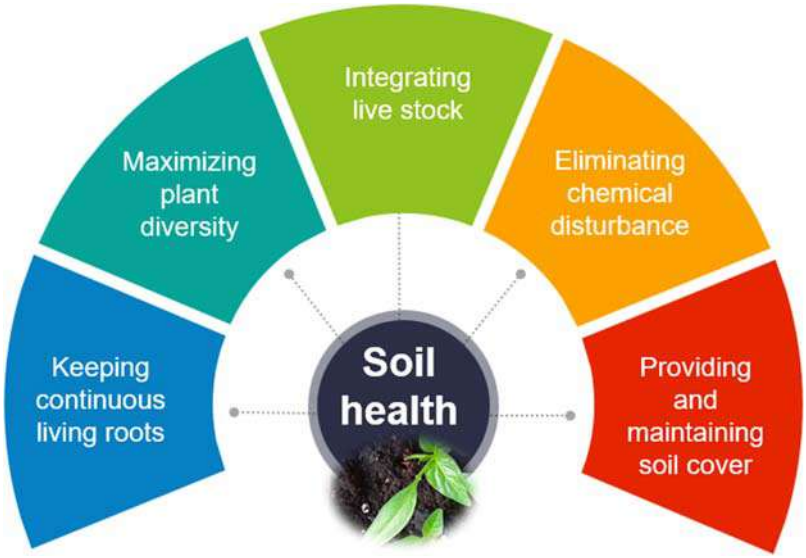
8.1 Introduction

Soil is a natural resource and an important agricultural input needed to sustain global production. Soil health is defined as the soil's ability to function as a vital living system within ecosystem and land use boundaries, supporting plant and animal production, maintaining or improving water and air quality, and promoting the health of plants and animals (Doran and Zeiss, 2000). Healthy soil is essential for food production, environmental quality, and overall ecosystem function. It encompasses a balance of physical, chemical, and biological properties that together support agricultural productivity, environmental sustainability, and resilience to climate change. Methods to improve soil health are explained in Figure 8.1.

Soil degradation is defined as the diminution of the current or potential capacity of soil to perform ecosystem services and functions, notably the production of food, feed, and fiber, as a consequence of the decline in the physical, chemical, and/or biological properties of soil (Diop *et al.*, 2022). Since soil degradation seriously damages species' natural habitats, it is one of the primary global causes of biodiversity loss (Kopittke *et al.*, 2021). Since soil degradation is closely linked to Earth system processes, crossing the soil planetary boundary would likely force other Earth system processes to exceed their limits as well. The process of soil degradation shown by various drivers, threats, and consequences is depicted in soil degradation, characterized by the decline in soil quality and productivity due to erosion, chemical contamination, loss of organic matter, and compaction, which poses a significant threat to global food security, biodiversity, and ecosystem health

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FIGURE 8.1 **Ways to improve soil health.**



(Gurmu, 2019). This degradation can have far-reaching consequences, affecting the natural environment, human livelihoods, and economies. Understanding the causes, processes, and impacts of soil degradation is essential for developing strategies to mitigate its effects and ensure sustainable land management practices (Keesstra *et al.*, 2018).

Soil degradation is a multifaceted problem driven by several factors. Addressing these causes requires a holistic approach that includes sustainable land management practices, policy interventions, and education to promote soil health (Powlson *et al.*, 2011). One of the most common forms of soil degradation, soil erosion, occurs when topsoil, rich in nutrients and organic matter, is removed by wind, water, or human activity. It is often exacerbated by deforestation, overgrazing, and poor agricultural practices like plowing and tilling, which disrupt soil structure, increasing erosion susceptibility (Kumar, Kumar, and Saikia, 2022). Soil compaction happens when soil particles are pressed together, reducing pore space. Major causes include heavy machinery, livestock trampling, and land overuse, and the compacted soil has poor water infiltration and drainage, leading to increased runoff, erosion, and reduced root growth. The use of chemical fertilizers and pesticides can degrade soil quality by altering its pH, killing beneficial microorganisms, and accumulating to toxic levels (Alengebawy *et al.*, 2021). Heavy metals from industrial activities and mining can also contaminate soils, posing a serious risk to plant and animal life. Intensive agricultural practices deplete soil organic matter, such as monocropping and removing crop residues. This depletion reduces soil fertility and water-holding capacity and increases vulnerability to erosion (Manna, Ghosh, and Acharya, 2003). Industrial activities release pollutants like heavy metals into the soil, reducing soil health and productivity. Urbanization seals soil surfaces with concrete and asphalt, disrupting natural water infiltration and soil respiration, contributing significantly to soil degradation (Dămătîrcă *et al.*, 2023). Climate change exacerbates soil degradation through more frequent and intense extreme weather events like heavy rainfall, floods, droughts, and hurricanes. These events accelerate erosion, compaction, and organic matter loss. Rising temperatures affect soil moisture levels and microbial activity, increasing soil susceptibility to degradation (Sierra *et al.*, 2015).

Soil erosion is a major threat to soil quality and function, defined as the process where earthen materials are worn away and transported by wind or water. Factors such as low organic matter, poor drainage, loss of soil structure, soil acidity, and salinization can trigger soil erosion (Osman, 2012). The increase in farmland due to global population growth exacerbates this issue, as it pressures the land, reducing soil cohesiveness and structure and making it more prone to erosion. Heavy farming equipment further compacts the soil, preventing water infiltration and increasing runoff. Human activities have degraded an estimated 2 billion hectares of land, with water erosion affecting 1,100 Mha and wind erosion affecting 550 Mha. Soil erosion specifically describes the gradual deterioration of the topsoil layer due to water, wind, and mass movement (Balasubramanian, 2017).

On the other hand, soil erosion describes how the topsoil, or topmost layer of soil, gradually deteriorates over time because of sluggish movement and transport caused by a variety of factors, primarily water, wind, and mass movement. The soil erosion process is depicted in Figure 8.2.

Soil erosion occurs in three stages: detachment, where the topsoil layer is separated from the earth's crust due to heavy rains, grazing, winds, and floods; transport, where the detached soil is moved from its original location by floods or other

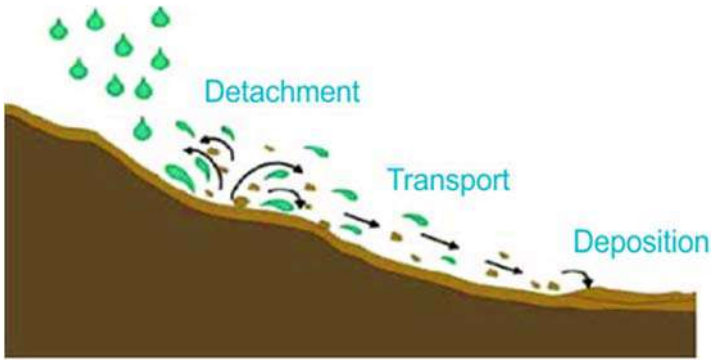


FIGURE 8.2 Soil erosion process.

forces; and deposition, where the soil settles in a new location. Soil erosion is a major problem that can harm the environment and human activities. However, it can be prevented using different management practices including terracing, crop rotation, and the use of cover crops.

8.2 Impact of agricultural activities on soil health

Agricultural interventions such as pesticides, mechanical tillage, and inorganic fertilizers impact soil biological communities, damage habitats, and disrupt soil functions to varying degrees (Kibblewhite, Ritz, and Swift, 2008). The resilience of soils to intensive agriculture varies with climate and topography, and the intensity of agricultural practices differs across farming systems, leading to diverse impacts on soil health (Naresh *et al.*, 2013). Table 8.1 lists common practices such as chemical pesticides, mechanical tillage, and inorganic fertilizers, along with their effects on soil health.

8.3 Significance of addressing agricultural waste in soil conservation

Agricultural waste amounts to billions of tons annually in both rich and developing nations. Animal manure, hulls, and shells taken from crops during mill processing and all leaves, straw, and husks left in the field after harvest are all considered agricultural residue (Cardoen *et al.*, 2015). Expanding agricultural production has naturally resulted in increased quantities of livestock waste, agricultural crop residues, and agro-industrial byproducts. The major area of agricultural waste generation is depicted in Figure 8.3.

TABLE 8.1 Impact of various agricultural activities on soil health conditions.

Agricultural activities	Impact	Reference
Mechanical tillage	Tillage is intended to substitute for biological plowing, and it is well known that earthworms are killed during this process.	(Landers, 2001)
Chemical fertilizers	Application of nitrogen or sulfur fertilizers caused a decrease in microbial count and soil pH.	(Alori, Adekiya and Adegbite, 2020)
Tillage	Soil levels of O, M, N, P, K, Ca, and Mg are reduced with increased tillage intensity.	(Adekiya, Agbede and Ojeniyi, 2016)
Inorganic fertilizers	The increased concentrations of nitrogen, potassium, and phosphate in farmlands because of extensive use of inorganic fertilizers.	(Masto *et al.*, 2007)
Clearing of native vegetation	Decline in soil organic matter, loss of ion-exchange capacity, decline in soil organic matter that reduces the capacity of the soil system to retain nutrients.	(Kibblewhite, Ritz and Swift, 2008)
Chemical fertilizers	It destroys soil crumbs, which results a highly compacted soil with reduced drainage and air circulation.	(Bitew and Alemayehu, 2017)

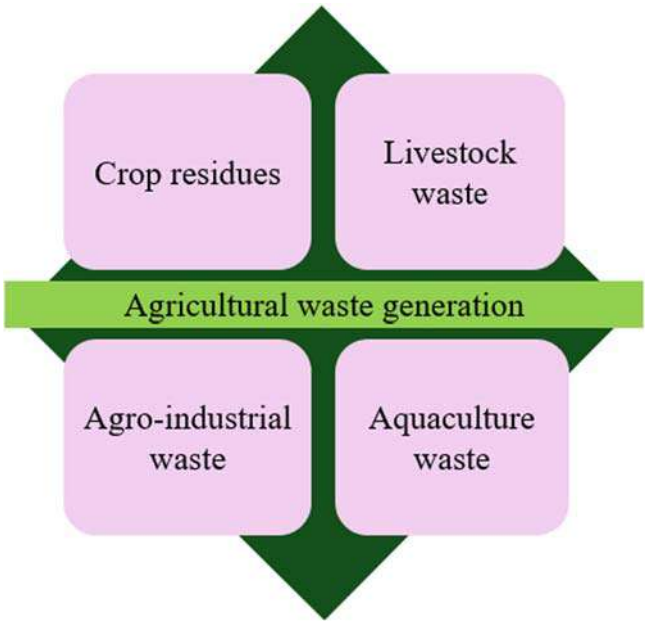


FIGURE 8.3 **Major areas of agricultural waste generation.**

Proper management and utilization of agricultural waste are crucial for environmental sustainability and soil health. Effective waste management can improve soil structure, enhance nutrient cycling, reduce erosion, and improve water retention, all essential for sustainable agriculture. Soil conservation, which protects soil from erosion and degradation, is vital for maintaining soil health and productivity. Healthy soils are the foundation of sustainable agriculture, supporting plant growth, nutrient cycling, and water regulation (Seifu and Elias, 2018). Soil degradation, marked by the loss of structure, nutrient depletion, and erosion, poses significant threats to agricultural productivity and food security.

8.4 Impact of agricultural waste on soil health

Agricultural waste, especially organic matter such as crop residues and animal manure, is rich in essential nutrients like nitrogen, phosphorus, and potassium. When these materials are returned to the soil, they decompose and release these nutrients, enriching the soil and enhancing its fertility. This process is crucial for maintaining soil nutrient balance and reducing the dependence on chemical fertilizers, which can have adverse environmental effects (Oluseun Adejumo and Adebukola Adebiyi, 2021). The organic matter from agricultural waste plays a pivotal role in improving soil structure. It increases soil porosity, allowing better air and water movement through the soil profile (Almendro-Candel *et al.*, 2018).

Improved soil structure enhances root penetration and water retention, which are vital for plant growth, and reduces soil compaction, a common issue in intensive farming. Crop residues left on the field act as protective cover, minimizing soil erosion by reducing the impact of raindrops and slowing surface runoff, allowing more water to infiltrate the soil and recharge groundwater aquifers. Adding organic waste to soil increases organic matter levels, enhancing soil health, productivity, and resilience to environmental stresses like drought and heavy rainfall.

8.5 Strategies for managing agricultural waste

Composting is one of the widely used methods to convert agricultural waste into valuable organic fertilizer, and it involves the decomposition of organic matter by microorganisms under controlled conditions. Compost, rich in nutrients and organic matter, significantly enhances soil fertility and structure while reducing waste volume and mitigating greenhouse gas emissions. Another method, mulching, involves covering the soil with organic materials like straw, leaves, or grass clippings to protect and enrich it (Prem *et al.*, 2020). This practice conserves soil moisture, reduces erosion, and suppresses weed growth. As the mulch decomposes, it adds organic matter and nutrients to the soil, further enhancing soil health.

Proper management of animal manure is essential to prevent environmental pollution and efficiently utilize its nutrients. Techniques such as anaerobic digestion, composting, and direct field application are commonly used. Anaerobic digestion not only reduces waste volume but also produces biogas, a renewable energy source (Holm-Nielsen, Al Seadi, and Oleskowicz-Popiel, 2009). Crop residues can be managed through practices such as no-till farming, cover cropping, and residue incorporation. No-till farming leaves crop residues on the soil surface, protecting it from erosion and improving soil structure. Cover cropping involves planting specific crops during the off-season to cover the soil, reduce erosion, and add organic matter (Kaspar and Singer, 2015). Incorporation of crop residues into the soil through plowing or disking helps in enhancing soil organic matter and nutrient levels.

8.6 Understanding agriculture waste as a resource

8.6.1 Global distribution of agricultural waste

According to recent statistics, the world produces about 1 billion tons of agricultural waste yearly, and agriculture alone contributes about one-fifth of greenhouse gas emissions (Karić *et al.*, 2022). Applying agricultural waste to developing and using alternative energy sources is crucial for researchers in sustainable energy and green development (Chen *et al.*, 2024). Farming and agricultural work across the world produces incredible amounts of crops, meat, and dairy to feed our hungry bodies. Yet, these practices also generate high volumes of agricultural waste. Global agricultural waste output is projected to rise significantly if emerging nations keep stepping up their farming practices (Obi, Ugwuishiwu, and Nwakaire, 2016).

The distribution of agricultural waste globally is shaped by agricultural practices, crop types, livestock density, and socioeconomic conditions. Proper waste management offers opportunities for environmental sustainability, economic growth, and social development. By converting agricultural waste into valuable resources through composting, bioenergy, soil amendment, and bio-based products, regions can tackle environmental challenges, boost agricultural productivity, and improve farmers' livelihoods. Effective waste management requires collaboration between governments, research institutions, and farmers, tailored to regional needs. These efforts can transform agricultural waste from a burden into a valuable resource, fostering a more sustainable and resilient agricultural system.

8.6.2 Types and sources of agricultural waste

Agricultural wastes are the wastes generated while processing agricultural raw products, such as crops, vegetables, fruits, poultry, meat, and dairy products. According to Obi, Ugwuishiwu, and Nwakaire (2016), agricultural wastes consist of crop residues (stalks, leaves, stems, and roots of crop), food processing waste (materials generated during the production, preparation, and processing of food), animal waste (solid manure, liquid slurry, animal carcasses, and processing waste), and agrochemical waste (pesticides, herbicides, fungicides, fertilizers, and other substances are used to boost crop production and protect plants pests and diseases).

8.6.2.1 Crop residues

India's current population stands at 1.4 billion and is expected to rise to 1.74 billion by 2050. To meet the increasing demand for food for this population, Indian agriculture produces 316 million tons of food grains in an area of 140 million ha. As a result, there is substantial rise in the production of crop residues. According to analyses by Bhuvaneshwari, Hettiarachchi, and Meegoda (2019), India generates over 686 million tons (Mt) of crop residue annually, with 368 Mt coming from cereal crops. Projections by Pavlenko and Searle (2019) estimate that this will increase to 868 Mt by 2030. Cereals, oilseeds, and sugarcane collectively account for the majority of crop residue, producing a total of 566 million tons (Mt). Fiber crops proportion is 10%, which generates 68 Mt of residues, while pulses contribute approximately 20 Mt. Among these, cereals are the largest contributors, with 359 Mt (55%) of the total crop residue, followed by sugarcane with 145 Mt (22%) (Tagade *et al.*, 2021). Out of a total of 686 Mt, 53.31% is utilized as fodder and 27.06% as fuel. Despite these uses, India still produces a surplus of 178 Mt of crop residue, with 87 Mt being burned (Dutta *et al.*, 2022; Kumar *et al.*, 2023). Therefore, it is essential to implement systematic approaches to effectively manage crop residue to prevent burning and mitigate its environmental impact.

8.6.2.2 Byproducts from food processing

To cater the needs of a growing population, a vast amount of food is processed at the industrial level, generating 25 to 30% waste from fruits and vegetables, including peels, seeds, pods, skins, hulls, cores, husks, and kernels. Improper handling of this waste harms the environment and soil. Today, various valorization techniques can convert this waste into

bioplastics, biofuels, bioenergy, organic acids, dietary fiber, protein, and bioactive compounds (Sarker *et al.*, 2024; Sharma, Xu, and Qin, 2019).

8.6.2.3 Livestock operations and animal waste

Livestock farming is crucial in India, which has the world's largest livestock population at 536.76 million, according to the 20th livestock census (Nehra and Jain, 2023). Livestock activities generate both solid (feed waste, manure, organic material) and liquid (urine, cage wash water, wastewater from animal bathing) waste. Typically, this waste is applied to agricultural land as fertilizer and soil conditioner to boost production (Green, 2019). However, excessive application or the use of inorganic fertilizers can lead to environmental damage and soil degradation. Consequently, many countries have developed guidelines for the proper use of animal waste.

8.6.2.4 Agrochemicals

To protect crops from epidemic diseases, large quantities of pesticides are used in agricultural fields, often leading to their misuse by farmers. Additionally, farmers frequently apply more fertilizer than necessary to boost crop production. The absorption of these fertilizers depends on the crop type, soil properties, and application methods (Hai and Tuyet, 2010). Excess fertilizer remains on the soil surface and can enter ponds, lakes, or rivers through surface runoff or irrigation, polluting both surface water and soil (Obi, Ugwuishiwu, and Nwakaire, 2016).

8.7 Environmental impact of agricultural waste accumulation

Agriculture activities are estimated to generate approximately 998 million tons of waste annually. Of the total solid waste produced on farms, about 80% is organic in nature. Commonly, farmers manage this substantial amount of waste by dumping it in pits, which helps to keep most of the land available for agricultural use (Maji *et al.*, 2020). Excess dumping of these agricultural wastes can lead to several environmental impacts and are discussed below.

8.7.1 Soil and water pollution

Diffuse pollution arises from accumulated contaminants from dispersed sources, rather than a single identifiable location. This often results from agricultural runoff, atmospheric deposition, and excess phosphorus, nitrogen, pesticides, and heavy metals (Birk, 2022). Consequently, this contamination degrades soil health and productivity and pollutes water bodies. Soils, often used as disposal sites for agricultural waste, diffuse pollutants into broader environmental ecosystems. These contaminants can be transported to rivers, streams, and reservoirs through runoff and soil erosion, affecting water quality and aquatic life. Additionally, deeper percolation of these materials can contaminate groundwater (Maji *et al.*, 2020; Obi, Ugwuishiwu, and Nwakaire, 2016).

The inherent properties of chemicals directly influence their movement within soil: those attached to soil particles move through erosion, while water carries the soluble ones. Properties like solubilization and adsorption complicate the assessment of their environmental impact. In addition, emerging contaminants such as microplastics, endocrine disruptors, human pathogens, and antibiotic-resistant genes pose significant threats to soil health (Petrie, Barden, and Kasprzyk-Hordern, 2015).

8.7.2 Methane emissions

Landfills of organic matter significantly contribute to methane emissions through anaerobic digestion, which occurs in three stages. First, fermentative bacteria hydrolyze complex organic matter into soluble molecules. Then, acid-forming bacteria convert these molecules into hydrogen, carbon dioxide, and simple organic acids like butyric, propionic, and acetic acids, as well as ethanol. Finally, methanogenic bacteria break down these acids into methane and carbon dioxide or reduce carbon dioxide with hydrogen to produce methane (Themelis and Ulloa, 2007). Similarly, in flooded rice fields, anaerobic decomposition occurs when water depletes oxygen in the soil by acting as a surface layer, creating conditions that allow methanogenic bacteria to produce methane.

The level of methane emissions from fields is influenced by factors such as the quantity of organic material and water management practices (Anand *et al.*, 2005). Moreover, agricultural activities such as open biomass burning, agricultural residue, savanna burning, and forest clearing also contribute to methane emissions (Karakurt, Aydin, and Aydiner, 2012). Anaerobic conditions in pits, ponds, or lagoons where organic manure or animal excreta are treated or stored can lead to methane emissions, with emission levels depending on factors such as manure composition, ambient temperature, and

storage type. Higher moisture content and temperatures result in increased methane emissions. Additionally, manure composition is influenced by the types of animals and their diets, collectively affecting methane emissions from manure management (Lusk, 1998).

8.7.3 Impact on biodiversity

Soil microorganisms, encompassing bacteria and other organisms, are vulnerable to the effects of bioactive hazardous substances found in the soil. Agricultural practices primarily release sulphonamides into the soil, where even small quantities can endanger human health and alter microbial populations (Baran *et al.*, 2011). Biosolids and sludge from households and food processing industries may harbor over 140 types of enteric viruses, bacteria, and parasites, influenced by factors like host immunity, pathogenicity, infection dose, environmental conditions, and resistance to treatment. While they can offer agricultural benefits, some, like pathogenic saprophytes, can harm plant growth and disrupt the soil microbiota (Boechat *et al.*, 2017).

8.7.4 Impacts of agricultural wastes on soil health

8.7.4.1 Soil contamination by pesticides, herbicides and fertilizers

The introduction of fertilizers reduces plant biodiversity and significantly diminishes the diversity of soil microbiota, encompassing fungi and bacteria. Moreover, fertilizers intended to enhance plant growth can alter soil osmolarity, pH levels, and carbon availability (Wang, Liu, and Bai, 2018), potentially leading to ion presence that induces soil toxicity, thereby decreasing Acidobacteria and Nitrospirae while slightly elevating Actinobacteria and Firmicutes levels. This decline in microbial diversity is often attributed to nitrogen addition through fertilizers (Kumar *et al.*, 2018). Application of fertilizers and pesticides releases heavy metals into the soil, including zinc, copper, iron, magnesium, cobalt, molybdenum, and selenium, beneficial for plants, animals, and microorganisms. However, high concentrations of non-nutritional heavy metals like arsenic, lead, and cadmium pose severe threats to organisms, despite small concentrations being conducive to the growth of superior organisms (Bruins, Kapil, and Oehme, 2000).

8.7.4.2 Soil contamination due to animal waste

Animal wastes, including livestock byproducts, urine, and feces deposited on soil surfaces, are often washed away during heavy rainfall, contaminating pastures and agricultural land. Elevated levels of *E. coli,* fecal coliforms, and total coliforms were detected in water samples contaminated with animal wastes due to the leaching of microorganisms into the soil and water (Akinbile *et al.*, 2016). Fertilizers of animal origin can alter the composition of soil microbiota, with copper from feed formulations contaminating the soil through excess leaching. While nitrogen and phosphorus in animal waste are beneficial in moderation, their excessive deposition can lead to nutrient imbalances in soil, affecting plant growth. Animal wastes also harbor pathogens like parasites, viruses, and bacteria, posing health risks to humans upon contact with contaminated soil and water (Singh and Rashid, 2017). Furthermore, the release of antibiotic residues into the soil from animal waste deposition can persist due to their long half-lives and water solubility, impacting soil microorganisms and contributing to antibiotic-resistance genes (Tasho and Cho, 2016). Ultimately, waste disposal adversely affects soil as toxins absorbed by the soil can enter the food chain through grazing animals, compromising productivity.

8.7.4.3 Soil acidification and salinization

Human activities across agricultural, industrial, and urban sectors heavily depend on pristine water resources and non-saline soil. However, in recent years, degradation and overuse of these resources have become prevalent in certain regions, with rapid salinization emerging as a significant threat capable of pushing ecosystems to the brink of collapse. Elevated salinity levels cause extensive and enduring harm, including biodiversity loss, desertification, soil dispersion, and hyper-salinity. Agroecosystems are particularly susceptible, as surpassing certain salinity thresholds sharply diminishes crop yields and food quality. Salinity often coincides with other environmental stressors like drought, waterlogging, pollution, acidity, and nutrient deficiencies, compounding challenges to ecosystem resilience and food security (Pereira, Barceló, and Panagos, 2020).

Soil acidification may result from organic matter accumulation, forming soluble complexes with cations like Ca^{2+} and Mg^{2+}, leading to their leaching and releasing H^{+} ions from dissociated functional groups. While organic matter accumulation primarily occurs in the top 10 cm, acidification often manifests below this depth (Bolan and Hedley, 2003). The impact of organic matter on soil pH depends on its composition, soil properties, and experimental conditions. Recent studies indicate that adding plant residues typically elevates acidic soil pH, with alkalinity production positively linked to

excess cations and total nitrogen in residues, and inversely correlated with initial soil pH. Processes such as organic anion mineralization, ammonification, nitrification, and proton association/dissociation influence soil pH. Although plant residue decomposition chiefly influences topsoil pH, root residues, with fewer excess cations, have a lesser impact on neutralizing subsurface acidity. Thus, plant residue decomposition primarily influences topsoil pH without necessarily inducing subsurface soil acidification (Tang, Weligama, and Sale, 2012).

8.7.4.4 Impacts of excess accumulation of crop residues

Improper use or excessive deposition of crop residues can lead to various environmental risks, such as nutrient overload (eutrophication), nutrient immobilization, soil salinization or acidification, groundwater contamination, and greenhouse gas emissions (McBride, 2022). Excessive deposition can also compact soil, hindering root growth by limiting air exchange. Heavy metals, being nonbiodegradable, persist in the soil, and frequent use of organic amendments like crop residues can increase metal accumulation. Although such amendments can initially reduce metal availability by forming complexes and soil aggregates, their degradation may reverse this effect, releasing metals and increasing their bioavailability. Moreover, crop residues can harbor pathogens and pests, potentially transferring them to subsequent crops and causing disease outbreaks among crop handlers. Additionally, crop residues with high lignin content decompose slowly and often promote weed growth (Tang, Weligama, and Sale, 2012).

8.7.4.5 Soil degradation due to byproducts from food processing

Disposing food processing byproducts into soil creates various agricultural and environmental challenges. These include soil compaction, erosion, contamination, nutrient depletion, and microbiota imbalance. Solid wastes or sludges from food processing industries are typically dense and heavy, impacting soil porosity and reducing water infiltration, leading to compaction. Improper wastewater discharge can cause soil erosion, resulting in topsoil runoff and reduced productivity (Petrie, Barden, and Kasprzyk-Hordern, 2015). Wastewater effluents, rich in organic matter, can initially enhance soil nutrition, but excessive accumulation may imbalance nutrients, acidify soil, and decrease fertility. Heavy metals and pesticide residues in food processing wastewater can percolate through soil, contaminating groundwater. Moreover, these effluents contain various microorganisms such as bacteria (*Salmonella* sp., *Shigella* sp., *Vibrio cholera, Campylobacter jejuni,* and *Escherichia coli*), enteric viruses (Rotavirus, Hepatitis A), enteroviruses (Poliovirus, Reovirus, Astrovirus, Calicivirus), protozoa (*Entamoeba histolytica*, *Cryptosporidium*, *Balantidium coli, Giardia lamblia, Toxoplasma gondii*), and helminths (*Trichuris trichiura, Ascaris lumbricoides*), posing significant health risks to humans (Boechat *et al.*, 2017).

8.8 Strategies for mitigating agricultural waste and soil degradation

Agricultural waste should be managed so that the residues will be used rapidly or stored so that they will not harm the environment or soil. The most important sustainable strategy for agricultural waste management to avoid soil erosion and degradation is to prevent the generation of waste, and another viable approach is the implementation of the "4-R" principle, that is, reduction, recovery, reuse, and recycling (Phiri, Mavinkere Rangappa, and Siengchin, 2024). However, judicious management is important as one technique is not feasible for all areas.

8.8.1 Sustainable agricultural practices

8.8.1.1 Composting

Composting breaks down organic matter using bacteria like *Pleurotus ostreatus* and *Phanerochaete chrysosporium,* producing valuable soil fertilizer. This process swiftly converts organic material into compost, known for its dark color and crumbly texture. Compost quality depends on biomass composition, C:N ratio, and environmental conditions. Composting crop residue offers a practical solution to address issues like increased greenhouse gas emissions, foul odors, heavy metal and antibiotic accumulation, soil and groundwater contamination, and the spread of pathogens and weed seeds (Greff *et al.*, 2022). Moreover, composting enhances productivity, improves disease resistance, and brings about various other positive outcomes.

8.8.1.2 Biochar

Agricultural waste can be converted into biochar, a carbon-rich, porous structure, through pyrolysis in the absence of oxygen or in an oxygen-depleted environment. India has the potential to produce around 212 Mt of biochar annually,

valued at approximately $500 billion, and this could reduce CO_2 emissions by 500 Mt annually (Windeatt *et al.*, 2014). Biochar offers diverse applications, including improving soil fertility, water retention, and nutrient absorption capacity (Kumar *et al.*, 2023). Research suggests biochar's potential to remove pollutants from wastewater, act as a catalyst, and serve as an energy storage device. However, commercial utilization of biochar hinges on infrastructure, supply chain management, crop residue collection and transportation, residue availability, and pretreatment costs.

8.8.1.3 Bioenergy production

Utilizing agricultural waste for bioenergy is gaining traction due to fossil fuel depletion and environmental concerns. Agricultural waste serves as feedstock for producing solid fuel (pellets, briquettes), liquid fuel (bio-oil, ethanol, methanol), and gaseous fuel (methane, producer gas) through thermochemical and biochemical conversion processes. First, second, and third-generation biofuels are generated from agricultural crop residues. The Indian government's initiative to increase ethanol blending in petrol to 20% by 2025 has spurred stakeholders' interest in using agricultural crop waste to reduce greenhouse gas emissions. Since agricultural crop residues consist of cellulose, hemicellulose, and lignin, pretreatment is necessary to remove lignin and make cellulose available during hydrolysis. Dutta *et al.* (2022) reported India's potential to produce approximately 51.3 billion liters of bioethanol annually from crop residue, with 65% coming from rice, wheat, and sugarcane. Similarly, biogas shows promising potential for generating energy from agricultural crop waste in India, especially for wastes with high moisture content (>60%).

8.8.1.4 Value-added products

Agricultural waste, consisting of starch, protein, lipids, water, hydrocarbons, cellulose, hemicellulose, lignin, and other elements like carbon, nitrogen, sulfur, and phosphorus, varies by waste type and environmental conditions (Kumar *et al.*, 2023). Lignocellulosic biomass typically contains 40 to 60% cellulose, 20 to 35% hemicellulose, and 15 to 30% lignin (Sharma, Xu, and Qin, 2019), making it suitable for producing value-added products such as enzymes (xylanase, amylases, pectinase, ligninases), probiotics, carbon fiber, dietary fiber, bioactive compounds, bioplastics, and various packaging materials (Farhat *et al.*, 2017). However, biomass pretreatment and hydrolysis are necessary, impacting yield and cost. Continued research is needed to enhance yield and economic viability.

8.8.1.5 Green construction materials

The construction industry faces environmental challenges due to the harmful emissions of toxic gases like COx and NOx and the extensive consumption of natural resources. There is a growing interest in developing green construction materials to address these issues and promote environmental sustainability. Recent studies have demonstrated the potential of using agricultural and industrial waste in concrete as replacements for cement, aggregate, and sand. For instance, Deraman *et al.* (2022) utilized agricultural waste such as sugarcane bagasse, coconut husk, and empty fruit bunches to produce roof board insulating material with enhanced physical and mechanical properties. Modani and Vyawahare (2013) found that incorporating 10% sugarcane bagasse ash (SBA) into concrete, with a water-cement ratio of 0.4 and 0.8% superplasticizer, yielded better results than without SBA. Additionally, researchers such as De Silva and Perera (2018) used rice husk ash (RHA) in clay bricks, reducing density and a 32.7% increase in compressive strength. These findings support developing sustainable construction practices by integrating agricultural waste materials.

8.8.1.6 Precision agriculture and use of technology to reduce waste

Managing agricultural waste in the field itself is an effective strategy as it reduces transportation costs, saves time, and returns essential nutrients to the soil. This can be achieved by either leaving crop residue on the surface or mixing it with the soil. Recent advancements in agricultural machinery, such as zero-till drills, mulchers, straw management systems (SMS), happy seeders, and rotary disc drills, allow direct sowing under crop residue without disturbing the soil. Retaining crop residue on the soil surface modifies soil and crop temperature, decreases evaporation, reduces irrigation needs, and mitigates soil erosion (Sidhu *et al.*, 2015). It also sequesters soil carbon and enhances crop resilience to terminal heat stress. Incorporating crop residue improves soil physical properties, fertility, organic carbon content, and enzymatic activity (Kumar *et al.*, 2023). Mulching with crop waste inhibits weed germination and growth, giving crops a competitive edge for nutrients and irrigation (Dutta *et al.*, 2022). However, retaining crop residue in zero-till systems can alter weed dynamics and promote weed seed accumulation in upper soil layers, reducing the efficacy of pre-emergence herbicides and necessitating higher chemical use. Future research should focus on developing effective weed control strategies, machinery for residue spreaders, and bio-decomposers for quicker residue mineralization to improve crop yields and increase the adoption of surface residue retention practices among farmers (Sidhu *et al.*, 2015).

8.9 Emerging trends in agricultural waste management

8.9.1 Production of functional foods and bioactive compounds from waste biomass

Byproducts from fruits and vegetables are often underutilized or discarded as organic waste. Food waste from industrial, agricultural, and domestic sources is steadily increasing, with losses of around 55 million metric tons in fruits and vegetables alone. This waste, including seeds, skin, rind, bracts, leaves, roots, bark, and pomace, is rich in bioactive compounds like pigments, polyphenols, dietary fibers, minerals, enzymes, and oils (Kainat *et al.*, 2022). These compounds have antibacterial, anticancer, antiviral, antimutagenic, and cardioprotective properties. There is significant potential to develop medicinal, nutraceutical, or functional food ingredients from these wastes, enhancing the nutritional profile and value of various food items (Yusuf, 2017). Extracting functional compounds from food waste reduces environmental pollution and enhances the value of functional food products. Traditional extraction techniques include Soxhlet extraction, hydrodistillation, and maceration, while novel methods such as supercritical fluid extraction, enzyme-assisted extraction, ultrasound-assisted extraction, and microwave-assisted extraction are also available (Table 8.2).

8.9.2 Production of enzymes

Waste biomass from agriculture, forestry, food, and municipal solid waste contains complex organic compounds that can produce enzymes through microbial fermentation. Food waste is particularly advantageous as it requires minimal pretreatment and no extra nutrient supplements. Two major bioprocesses for enzyme production are submerged fermentation and solid-state fermentation. Submerged fermentation involves microorganisms thriving on soluble and insoluble substrates within a liquid medium (Kapoor, Panwar, and Kaira, 2016). In solid-state fermentation, microorganisms grow on solid, moist substrates without a free aqueous phase. Solid-state fermentation is more energy-efficient than submerged fermentation (Lin *et al.*, 2013). Enzymes like cellulases, proteases, amylases, lipases, xylanase, laccase, tannase, chitinase, and pectinases can be produced from waste biomass (Kapoor, Panwar, and Kaira, 2016). These enzymes have various industrial applications and potential uses in biorefinery operations for biofuel and chemical production.

Production of nanomaterials from waste

Producing nanomaterials from agricultural waste offers a sustainable method for waste valorization and material synthesis. Nanocellulose, derived from agricultural wastes like citrus and orange peels, presents a sustainable alternative for waste management. Despite its potential, efficient extraction techniques and diverse biological science applications remain challenging (Sangeetha *et al.*, 2017). Silica nanoparticles can be synthesized from agricultural wastes such as corn hub, bagasse ash, and rice husk, with significant agricultural applications. Corn, a major global crop, provides substantial agrowaste for silica nanoparticle production. Silica nanoparticles have also been synthesized from wheat straw and rice husk using environmentally friendly methods (Ghorbani, Sanati, and Maleki, 2015). Carbon-rich agricultural residues like rice husk, wheat straw, and coconut shells can be pyrolyzed or hydrothermally treated to produce carbonaceous nanomaterials such as carbon nanotubes and graphene (Sangeetha *et al.*, 2017).

TABLE 8.2 Bioactive compounds from biomass residues.

Bioactive compound	Source	Reference
Dietary fibers	Potato peel, Potato solid waste, Apple peel, Apple pomace, Mango peel, Lemon peel	(Amin *et al.*, 2023; Ncobela *et al.*, 2017)
Phenolic compounds	Potato peels, Cucumber peels, Tomato peels, Watermelon peels, Citrus trash, Banana peels, Apple peels, Grape skins and seeds	(Azizi *et al.*, 2020)
Organic acids	Cassava bagasse, Apple pomace, Potato peel, Sweet corn residues, Mango residues	(Ain *et al.*, 2020; Khandagale *et al.*, 2021)
Proteins	Papaya peels, Avocado peels, Kiwifruit peels, Citrus peels, Apple pomace, Carrot pomace; Green pea peels, Mosambi peel, Tomato solid waste, Potato solid waste, Cabbage leaves, Pineapple peels, Mango peels	(Negro, Ruggeri, and Fino, 2018; Srivastava *et al.*, 2021)

8.9.4 Utilization of agri-wastes for packaging

Agricultural wastes can be used to produce polymers and fibers for bioplastic packaging, containers, trays, and food coatings. Utilizing agri-food waste and byproducts such as bagasse, pulps, roots, shells, straws, and wastewater allows for the sustainable extraction and isolation of biopolymers, which can be transformed into eco-friendly packaging materials such as bioplastics, biofilms, paper, and cardboard (Cristofoli *et al.*, 2023). Biopolymers are classified into protein-based, starch-based, cellulose-based, chitin-based, lipid-based, and microbial-based categories. Key sources for bioplastic production include wheat, corn, and soy proteins, as well as starch from corn, cassava, wheat, rice, peas, tapioca, and potatoes. Lignocellulose is abundant in trees and agricultural waste, while fish scales, crab shells, and prawn shells are prime sources for chitin (Duan *et al.*, 2018). Microorganisms can also use agricultural and food waste as feedstock for fermentation to produce biopolymers (Brodnjak, 2016).

8.9.5 Application of waste biomass for wastewater treatment

The demand for natural and sustainable water treatment methods is rising, leading to the exploration of low-cost adsorbents from agricultural waste like stems, husks, and nut shells (Tiwari, Pal, and Prasad, 2022). Materials such as activated carbon, derived from byproducts like olive stones, bamboo dust, and rice husks, have proven effective in eliminating organic pollutants from water (Anfar *et al.*, 2020). Agricultural waste biomass can efficiently treat polluted water by mitigating toxins and microbial contamination, enhancing water quality (Tiwari, Pal, and Prasad, 2022). Innovative techniques repurpose food and agricultural waste as adsorbents, filters, or biological agents for wastewater treatment.

8.9.6 Sustainable agriculture through technological innovations

Increasing agricultural production with limited resources is a major challenge. The integration of innovative technologies such as precision agriculture, artificial intelligence (AI), the Internet of Things (IoT), machine learning, big data analytics, cloud computing, drones, and genome editing is essential for sustainable production and crop management (Sarfraz *et al.*, 2023). Precision agriculture uses GPS, sensors, and IoT to optimize crop management, enhancing productivity and reducing resource wastage. Drones and satellite imaging provide real-time monitoring of field health and infestations. Automated machinery increases productivity and precision. Genetically modified crops resist pests and diseases, leading to higher yields. Sustainable practices like water management, integrated pest management, and blockchain traceability also reduce waste and improve the agricultural sector.

8.10 Conclusion

The intricate relationship between agricultural waste and soil health underscores the urgent need for sustainable soil conservation practices. The challenges posed by soil degradation and erosion, driven by various agricultural activities such as waste deposition, highlight the critical importance of managing agricultural waste effectively. Sustainable practices such as conservation tillage, precision agriculture, terracing, and agroforestry are essential for mitigating the negative impacts of agricultural waste on soil health. Additionally, addressing these issues requires a multifaceted approach that includes use of novel technologies for processing waste, education, public awareness, and policy support. By embracing technological innovation, we can ensure the resilience and fertility of soils against the pressures of agricultural intensification, securing a sustainable future for agricultural production and ecosystem stability.

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Chapter 9

Pyrethroids contamination: Understanding the impacts on freshwater invertebrates and fish

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Chapter Outline

9.1. Introduction 137
9.2. Evolution of pyrethroids generations 138
9.3. Uses of pyrethroids 138
9.4. Mode of actions 138
9.5. Transport, persistence, and bioavailability in water 139
9.6. Effects on freshwater invertebrates 140
9.7. Effects on tadpoles of Amphibia 143
9.8. Effects on freshwater fish 143
9.9. Future research scopes 148
9.10. Conclusion 148
References 148

9.1 Introduction

Agricultural intensification in modern agriculture plays a pivotal role in satisfying global demand for food to feed the world's fast-growing population and in achieving food security. In recent years, remarkable advances in genetics and plant breeding have bestowed high-yielding crop varieties on various sectors of agriculture, resulting in massive crop production and providing a solution to the world's increasing demand for food grains. However, it has encouraged the pervasive use of pesticides in agricultural fields to protect crops. As insect pests become resistant to the recommended dose and type of insecticide, higher doses and new pesticides and formulations/combinations of insecticides were prescribed for better field efficacy without regard for the environment or the fate of non-target organisms exposed to these pesticides. Only a tiny fraction of the total pesticides used on crops—less than 0.1%—reach the intended targets; the remainder enters the environment (Tudi *et al.*, 2022). Pesticides and their bio-transformed products are found to be present everywhere in the environment, and depending on their nature, chemical makeup, dosage, and intended targets, they may persist and interact with the environment and living things in a variety of ways. Pesticides represent a potential risk to both animals and humanity owing to their high persistence, ability to bioaccumulate, and adverse effects on the organisms connected with the food chain (Kumar *et al.*, 2023).

In the late 1970s, synthetic pyrethroids were introduced in the market as an alternative to organochlorines, organophosphates, and carbamates. Currently, synthetic pyrethroids account for over 25% of the worldwide pesticide market. The high bio-efficacy of pyrethroids, which necessitates a minimal dose during field application, along with their poor water solubility, photolabile nature, and strong sorption, eventually reduces their potential bioavailability in nature (Antwi and Reddy, 2015). The way they are formulated, combined with other pesticides, and used has changed significantly over the past few decades. This effectively controlled the insect population in agricultural fields and increased agricultural productivity, but it was not without negative environmental repercussions. Concern regarding the potential ecological effects of pyrethroids on fish and other aquatic invertebrates has grown as a result of their growing use. Pyrethroid residues have been found in surface water, sediments, and fish tissues. The risk of fish in ponds, rivers, and reservoirs rises due to pyrethroid contamination, affecting both yield and quality. As aquatic organisms, fish, crustaceans, and mollusks are the

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most affected organisms because they may survive in a variety of aquatic habitats, are highly sensitive to contaminants even at low concentrations, and form interconnected aquatic food chains and food webs (Ranatunga *et al.*, 2023). Herein, the effects of pyrethroids on fish and other aquatic invertebrates linked to delicate food webs in aquatic ecosystems have been detailed.

9.2 Evolution of pyrethroids generations

Pyrethroids, synthetic derivatives of pyrethrins found in the natural extract of dried chrysanthemum flower (*Chrysanthemum cinerariaefolium*), have gradually replaced conventional pesticides due to concerns about their toxicity and persistence on a global scale (Casida, 1980). Natural extracts and the first pyrethrin derivatives have long been used successfully to manage household and storage pests. However, due to their instability in light and air conditions, these compounds proved ineffective against agricultural pests in field conditions. Because of this, synthetic pyrethroids in different modified forms were introduced in the market with better efficacy in killing target pests in the field. The presence of an acid moiety, a central ester bond, and an alcohol moiety are among the common characteristics shared by all pyrethroids. In some pyrethroids, the cyclopropane carboxylic acid has been altogether replaced by another group to develop broad-spectrum activity against a variety of insects (Aznar-Alemany and Eljarrat, 2020). These non-cyclopropanoid pyrethroids are relatively stable in visible light. In some other pyrethroids, the α-cyano group is added to the alcohol moiety (cypermethrin, deltamethrin, and fenvalerate), and that becomes even more toxic. The halogenated compounds (decamethrin, cyfluthrin, and cyhalothrin) render better residual toxicity to insects and are thus a concern for the environment. However, the toxicity of a pyrethroid depends on modifications to its structure, stereochemistry, and formulation (Aznar-Alemany and Eljarrat, 2020). Most of the pyrethroids are a mixture of several geometric and optical isomers. Cis isomers have been found to be more toxic than trans isomers for mammals. Two distinct categories of pyrethroids have been found depending on the nature of their toxicity and molecular structure with or without the α-cyano group (Ray and Forshaw, 2000). Allethrin, resmethrin, permethrin, bifenthrin, tefluthrin, metofluthrin, tetramethrin, etc., are listed as Type I pyrethroids, while Type II pyrethroids include esfenvalerate, fenvalerate, λ-cyhalothrin, cyfluthrin, cypermethrin, deltamethrin, etc. (Palmquist *et al.*, 2012). Type II pyrethroids with the α-cyano group have higher neurotoxicity compared to Type I pyrethroids without the α-cyano group (Kaviraj and Gupta, 2014). Allethrin is classed as a first-generation Type I pyrethroid, resmethrin as a second-generation Type I pyrethroid, permethrin as a third-generation Type I pyrethroid, fenvalerate as a third-generation Type II pyrethroid, and bifenthrin as a fourth-generation Type I pyrethroid, whereas cyhalothrin, cypermethrin, and deltamethrin are fourth-generation Type II pyrethroids (Roy, 2002; Soderlund *et al.*, 2002).

9.3 Uses of pyrethroids

Pyrethroids are extensively used as broad-spectrum insecticides against agricultural and household insect pests belonging to the orders Coleoptera, Diptera, Hemiptera (Homoptera and Heteroptera), Hymenoptera, Lepidoptera, Orthoptera, and Thysanoptera (Dhuldhaj *et al.*, 2023). Their use in household sprays, insect repellents, veterinary sprays and shampoos, aerosol bombs, and lice treatments is quite common. They are increasingly being used in public health. The World Health Organization (WHO) recommended the usage of α-cypermethrin, bifenthrin, cyfluthrin, deltamethrin, etofenprox, and λ-cyhalothrin in indoor residual spraying; α-cypermethrin, cyfluthrin, deltamethrin, etofenprox, λ-cyhalothrin, and permethrin in treating mosquito nets; and permethrin and D-phenothrin in aircraft disinsection (World Health Organization, Safety of pyrethroids for public health use, 2005). Table 9.1 and Table 9.2 present the molecular formula, IUPAC name, uses, and class of Type I and Type II pyrethroids, respectively. The molecular formula, IUPAC name, and uses were taken from PubChem (https://pubchem.ncbi.nlm.nih.gov), whereas for the pyrethroid class, the WHO (2019) recommended classification of pesticides by hazard was followed. All over the world, Type II synthetic pyrethroids are mostly applied in agricultural fields for pest control (Kaviraj and Gupta, 2014). The pyrethroids market has increased significantly in recent years. It will increase from $3.71 billion (2023) to $3.92 billion (2024), with a compound annual growth rate (CAGR) of 5.75%. The market's largest region is Asia-Pacific (Pyrethroids Global Market Report, 2024).

9.4 Mode of actions

Synthetic pyrethroids kill insects by targeting the nervous system (Field *et al.*, 2017). Pyrethroids alter the permeability of the nerve membrane to sodium (Na^+) and potassium (K^+) ions, disrupting the activities of voltage-gated sodium channels. As a result, more sodium ions penetrate the membrane, depolarizing the neural membrane more than usual (Soderlund,

TABLE 9.1 Type I synthetic pyrethroids: Molecular formula, IUPAC name, uses.

Pyrethroids	Molecular formula	IUPAC name	Uses	Class
Allethrin	$C_{19}H_{26}O_3$	(2-methyl-4-oxo-3-prop-2-enylcyclopent-2-en-1-yl) 2,2-dimethyl-3-(2-methylprop-1-enyl)cyclopropane-1-carboxylate	Effective against flies, mosquitoes, other household insect pests, and ectoparasites. Also used in pet shampoos.	II
Tetramethrin	$C_{19}H_{25}NO_4$	(1,3-dioxo-4,5,6,7-tetrahydroisoindol-2-yl) methyl 2,2-dimethyl-3-(2-methylprop-1-enyl)cyclopropane-1-carboxylate	Acts as an insecticide in home, public health, gardens.	U
Resmethrin	$C_{22}H_{26}O_3$	(5-benzylfuran-3-yl)methyl 2,2-dimethyl-3-(2-methylprop-1-enyl)cyclopropane-1-carboxylate	Insecticides, including both household and public health pests, are also used for fabric protection, pet sprays, and shampoos.	III
Phenothrin	$C_{23}H_{26}O_3$	(3-phenoxyphenyl)methyl 2,2-dimethyl-3-(2-methylprop-1-enyl)cyclopropane-1-carboxylate	Insecticides, primarily for stored grain pests, are effective against fleas, ticks, ants, and head lice in humans and have sanitary uses.	U
Permethrin	$C_{21}Cl_2H_{20}O_3$ $C_{21}H_{20}Cl_2O_3$	(3-phenoxyphenyl)methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate	Used as insecticides, acaricides, and also in the treatment of lice infestations and scabies.	II
Bifenthrin	$C_{23}H_{22}ClF_3O_2$	(2-methyl-3-phenylphenyl)methyl (1R,3R)-3-[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropane-1-carboxylate	Acts as a broad-spectrum insecticide, termiticide, and acaricide (including mites).	II
Tefluthrin	$C_{17}H_{24}ClF_7O_2$	(2,3,5,6-tetrafluoro-4-methylphenyl)methyl (1S,3S)-3-[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropane-1-carboxylate	Insecticide for a variety of insect pests, belonging to the orders Coleoptera, Lepidoptera, and Diptera, that attack maize, sugar beet, wheat, field corn, popcorn, seed corn, sweet corn, and other crops.	Ib

From Pubchem and class "WHO recommended classification of pesticides by hazard and guidelines to classification, 2019 edition. Geneva: World Health Organization," 2019.

2010). All these ultimately may lead to alteration of nerve functioning. Voltage-gated sodium channels are the primary target sites of pyrethroids (Ravula and Yenugu, 2021). The functioning of gamma amino butyric acid (GABA)-gated chloride channels, voltage-dependent chloride channels, ATPase and voltage-gated calcium channels, calcium-dependent neurotransmitter release, and PKC-dependent protein phosphorylation are all modulated by Type II pyrethroids (Ravula and Yenugu, 2021; Soderlund, 2010). Type I pyrethroids work by altering the configuration of sodium channels in neuronal membranes during their opening and shutting, resulting in tremor-type syndrome (T), which is characterized by hyperexcitation, tremors, and prostration. On the other hand, Type II pyrethroids lead to stimulus-dependent nerve depolarization and nerve blockade and induce motor impairment, salivation, and choreoathetosis-salivation syndrome (CS) (Chrustek *et al.*, 2018). As Type II pyrethroids possess the α-cyano-3-phenoxybenzyl moiety, they are more toxic than Type II pyrethroids (Rodrigues *et al.*, 2023). Pyrethroids operate in a stereospecific manner on voltage-gated sodium channels (Lund and Narahashi, 1982), and their stereoisomers that interfere with the functionality of voltage-gated sodium channels also exhibit potent insecticidal or toxicological effects (Ray and Forshaw, 2000). Pyrethroids show low toxicity to mammals and birds compared to fishes and insects because of faster detoxification and lower intestine absorption in homeotherms (Sapana Devi and Gupta, 2014). In mammals, pyrethroids undergo rapid metabolic degradation through ester hydrolysis by carboxylesterases and oxidation by cytochrome P450 (CYP) enzymes (Kaneko, 2011).

9.5 Transport, persistence, and bioavailability in water

Synthetic pyrethroids enter the water bodies either via agricultural runoff or spray drift (Prusty *et al.*, 2015). Pyrethroid is hydrophobic. Once they enter the aqueous medium, they quickly disperse from the dissolved water phase and will be readily adsorbed to sediment and suspended soil particles and plants (Diegelmann *et al.*, 2015; Majumder and Kaviraj, 2021). However, pyrethroid accumulation in sediment can act as a threat to benthic invertebrates. Pyrethroids that remain dissolved in water are the bioavailable form, and that can pose a risk to pelagic zooplankton, fish, and other animals living there

TABLE 9.2 Type II synthetic pyrethroids: Molecular formula, IUPAC name, uses.

Pyrethroids	Molecular formula	IUPAC name	Uses	Class
Fenvalerate	$C_{25}H_{22}ClNO_3$	[cyano-(3-phenoxyphenyl)methyl] 2-(4-chlorophenyl)-3-methyl butanoate	It controls chewing, sucking, and boring insects in various crops. It is also used in public health and animal husbandry.	II
Cypermethrin	$C_{22}H_{19}C_{l2}NO_3$	[cyano-(3-phenoxyphenyl)methyl] 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate	A broad-spectrum insecticide is used to control a wide range of chewing and sucking insects in fruits, vegetables, vines, cereals, maize, cotton, rice, other crops, and forestry. Cypermethrin is also registered for use on industrial, commercial, and residential sites. It is also used to control ants, termites, cockroaches, fleas, other insects, and animal ectoparasites.	II
Deltamethrin	$C_{22}H_{19}Br_2NO_3$	[(S)-cyano-(3-phenoxyphenyl)methyl] (1R,3R)-3-(2,2-dibromoethenyl)-2,2-dimethylcyclopropane-1-carboxylate	The majority of its application is in crop protection; cotton receives 45% of its usage, followed by fruit and vegetable crops at 25%, cereals, maize, and soybeans at 20%, and other crops including coffee, maize, and hops at 10%. In addition, it is employed in public health initiatives and for the protection of stored crops. Additionally, it is employed as an animal ectoparasite, a wood preservative, and a pest control agent for household flying and crawling insects.	II
Cyfluthrin	$C_{22}H_{18}Cl_2FNO_3$	[cyano-(4-fluoro-3-phenoxyphenyl) methyl] 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate	Controlling chewing and sucking insects on crops including cotton, turf, ornamentals, hops, cereal, corn, deciduous fruit, peanuts, potatoes, and other vegetables has been its main usage in agriculture. Additionally employed for structural pest control and in public health.	Ib
Cyhalothrin	$C_{23}H_{19}ClF_3NO_3$	[cyano-(3-phenoxyphenyl)methyl] 3-[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropane-1-carboxylate	Applied as an insecticide, an acaricide (or miticide), and in vector control.	II

From Pubchem and class "WHO recommended classification of pesticides by hazard and guidelines to classification, 2019 edition. Geneva: World Health Organization," 2019.

(Méjanelle *et al.*, 2020). Pyrethroid residues have been reported to be present both in surface water and in sediments (Feo *et al.*, 2010). Pyrethroid bioavailability and its aquatic toxicity have been presented in Figure 9.1. Pyrethroids undergo photodegradation within 1 to 2 days; in a few cases, the photodegradation span may differ (Galadima *et al.*, 2021). Microbes and sunlight are the two key contributors to their photodegradation, both in soil and in surface water. A common photodegradation product is 3-phenoxybenzoic acid, which is more toxic than the parent pyrethroid compound (Zhu *et al.*, 2020).

9.6 Effects on freshwater invertebrates

Planktons play a crucial role in the aquatic food chain. Information regarding the effects of pyrethroids on various types of zooplankton has some importance for a wider understanding of the environmental risks of pyrethroids (Ranatunga *et al.*, 2023). Several studies have reported that copepods are found to be more susceptible to pyrethroids than cladocerans and rotifers (Sharma *et al.*, 2014). *Cyclops viridis*, a copepod, was reported to be highly sensitive to cypermethrin (96 h LC_{50}: 0.04 and 0.08 μg/L for emulsifiable concentrate (10%) and technical grade cypermethrin, respectively (Majumder and Kaviraj, 2015). Saha and Kaviraj (2008) observed the susceptibility of another copepod, *Diaptomus forbesi*, to 10% EC of cypermethrin (96 h LC_{50}: 0.03 μg/L). Much higher LC_{50} values of pyrethroids were reported in Cladoceran zooplankton

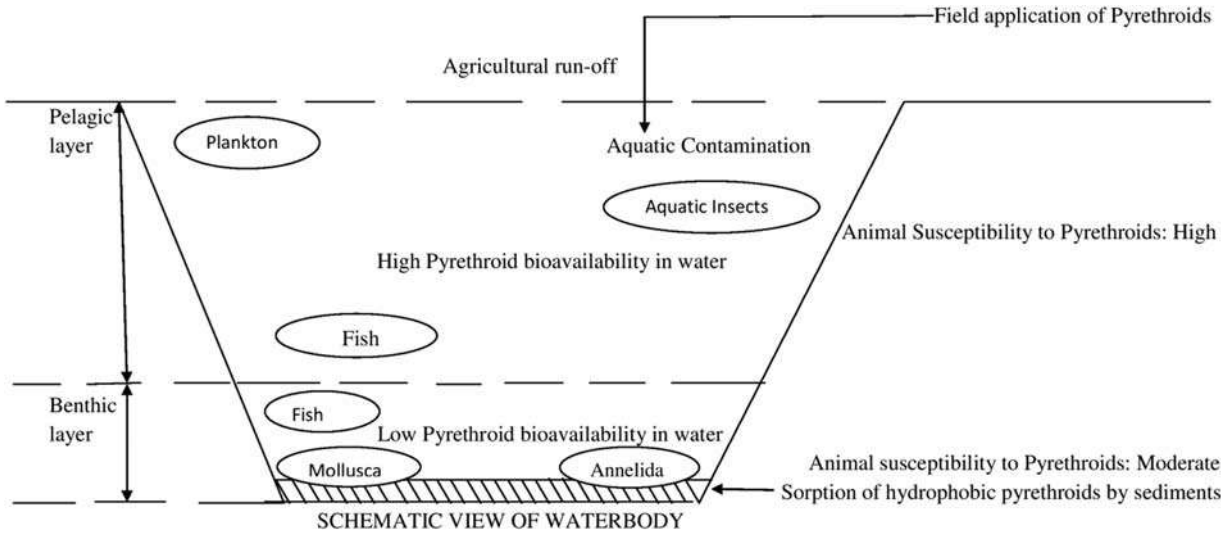


FIGURE 9.1 **Pyrethroid bioavailability and aquatic toxicity.** Pyrethroids undergo photodegradation within 1 to 2 days; in a few cases, the photodegradation span may differ. Microbes and sunlight are the two key contributors to their photodegradation, both in soil and in surface water. A common photodegradation product is 3-phenoxybenzoic acid, which is more toxic than the parent pyrethroid compound.

Daphnia magna by Rodrigues *et al.* (2023): 24 h LC_{50} deltamethrin: 64.13 μg/L and Demetrio *et al.* (2014): 48 h LC_{50} cypermethrin: 2.81 μg/L. Rotifers stand as the most tolerant to pyrethroids among the crustacean zooplankton. Sánchez-Fortún and Barahona (2005) reported 24 h LC_{50} of cypermethrin to *Brachionus calyciflorus* and *Brachionus plicatilis* as 80 μg/L and 300 μg/L, respectively. Clark *et al.* (1989) recorded a 96 h LC_{50} value of cypermethrin (below 0.01 μg/L) for several marine invertebrates. Aquatic insects also show pyrethroid sensitivity: *Ranatra filiformis* (96 h LC_{50} value of cypermethrin: 0.065 μg/L; Saha and Kaviraj, 2008); *Callibaetis radiates* (24 h LC_{50} value of deltamethrin: 0.60 μg/L (Gutiérrez *et al.*, 2016). Comparative pyrethroid studies in freshwater shrimp (*Gammarus pulex*: 96 h LC_{50} of deltamethrin: 0.068 μg/L), crayfish (*Procambarus* sp: 96 h LC_{50} of deltamethrin: 0.03−0.21 μg/L; Lidova *et al.*, 2019); 96 h LC_{50} of cypermethrin: 0.17−0.18 μg/L (Lidova *et al.*, 2019); *Astacus leptodactylus*: 96 h LC_{50} of permethrin: 0.903 μg/L (Günal *et al.*, 2021), and prawn (*Macrobrachium* sp.: 96 h LC_{50} of λ-cyhalothrin: 0.04−0.066 μg/L; Bhavan *et al.*, 2015) also indicated high pyrethroid toxicity where 96 h LC_{50} value <0.01 μg/L in the majority of the cases (Table 9.3).

Cypermethrin reduced total protein content in tissues of the hepatopancreas, ovary, gill, intestine, and muscle of the freshwater crab *Barytelphusa cunicularis* (Joshi and Kulkarni, 2011). Deltamethrin can change midgut cytomorphology and disturb nerve impulse transmission in the instars of mayflies, *Callibaetis radiates* (Gutiérrez *et al.*, 2016). Glycogen depletion and DNA damage in *D. magna* due to deltamethrin assault were reported by Rodrigues *et al.* (2023). Because of their close taxonomic relatedness to insects, crustaceans are more vulnerable to the effects of pesticides, like insect pests (Roque *et al.*, 2005). They are susceptible to neurotoxicants, since their biological pathways are comparable to those of insects and probably lack a pyrethroid-metabolizing mechanism (Majumder and Kaviraj, 2015).

In freshwater benthic environments, oligochaetes are essential for the decomposition of organic matter. They also serve as prey for fish and other invertebrates, which helps transfer pollutants to higher trophic levels. For these reasons, oligochaetes are more widely accepted as bioindicators of pyrethroids in sediment (Rosa *et al.*, 2016). *Branchiura sowerbyi,* an oligochaete worm, was shown to be moderately sensitive to pyrethroids: Majumder and Kaviraj (2015) observed that the cypermethrin's 96 h LC_{50} as 75 μg/L; similarly, the bifenthrin's 96 h LC_{50} was 1.043 μg/L (Table 9.3). The immobility and hypersecretion of mucous seen in the tubificid worms exposed to pyrethroids were reported by several workers (Majumder and Kaviraj, 2015). Esfenvalerate exposure for 28 days had an impact on *Lumbriculus variegates,* an oligochaete, in terms of both biomass and reproduction (Rosa *et al.*, 2016).

Freshwater molluscs like mussels and snails that play an important role in maintaining the water body as a natural cleaner is a boon for fish farmers (Bakshi *et al.*, 2023). However, pesticide contamination moderately affects them. The gastropod *Pila globosa* was found to be sensitive to cypermethrin, 96 h LC_{50} value of commercial cypermethrin being 545 μg/L (Majumder and Kaviraj, 2015). Only a few reports are available on cypermethrin toxicity to mollusks (Table 9.3). The 96 h LC_{50} value of cypermethrin to *Katelysia opima*, an estuarine clam, and *Lamellidens marginalis,* a freshwater mussel, the same is 2750 μg/L (Mukadam and Kulkarni, 2014) and 20,300 μg/L (Kumar *et al.*, 2012), respectively. Pal and Bej (2019) reported the 96 h LC_{50} value of α-cypermethrin to *Bellamya bengalensis* is 15 μg/L. During cypermethrin

TABLE 9.3 Median lethal concentration LC_{50} values (μg/L) of different pyrethroids to aquatic invertebrates.

Pyrethroid	Species	Hour	LC_{50}	Reference
Deltamethrin	*Callibaetis radiatus*	24	0.60	(Gutiérrez *et al.*, 2016)
Deltamethrin	*Daphnia magna*	24	64.13	(Rodrigues *et al.*, 2023)
Deltamethrin	*Gammarus fossarum*	96	0.0332	(Adam *et al.*, 2010)
Deltamethrin	*Gammarus pulex*	96	0.068	(Adam *et al.*, 2010)
Deltamethrin	*Procambarus virginalis*	96	0.21	(Lidova *et al.*, 2019)
Deltamethrin	*Procambarus clarkii*	96	0.16	(Lidova *et al.*, 2019)
Deltamethrin	*Pacifastacus leniusculus*	96	0.03	(Lidova *et al.*, 2019)
Deltamethrin	*Orconectes limosus*	96	0.76	(Lidova *et al.*, 2019)
Deltamethrin	*Cherax destructor*	96	0.27	(Lidova *et al.*, 2019)
Deltamethrin	*Unio elongatulus eucirrus*	96	6600	(Köprücü and Seker, 2008)
Cypermethrin	*Daphnia magna*	48	2.81	(Demetrio *et al.*, 2014)
Cypermethrin	*Hydra attenuata*	96	9900	(Demetrio *et al.*, 2012)
Cypermethrin	*Spiralothelphusa hydrodroma* (Herbst)	96	1315	(Sreenivasan *et al.*, 2011)
Cypermethrin	*Unio elongatulus eucirrus*	96	59.20	(Köprücü *et al.*, 2010)
Cypermethrin	*Hyalella curvispina*	48	0.066	(Mugni *et al.*, 2013)
Cypermethrin	*Procambarus virginalis*	96	0.18	(Lidova *et al.*, 2019)
Cypermethrin	*Procambarus clarkii*	96	0.17	(Lidova *et al.*, 2019)
Cypermethrin	*Pacifastacus leniusculus*	96	0.19	(Lidova *et al.*, 2019)
Cypermethrin	*Orconectes limosus*	96	0.09	(Lidova *et al.*, 2019)
Cypermethrin	*Cherax destructor*	96	0.30	(Lidova *et al.*, 2019)
Cypermethrin	*Diaptomus forbesi*	96	0.03	(Saha and Kaviraj, 2008)
Cypermethrin	*Ranatra filiformis*	96	0.065	(Saha and Kaviraj, 2008)
Cypermethrin	*Branchiura sowerbyi*	96	75	(Majumder and Kaviraj, 2015)
Cypermethrin	*Cyclops viridis*	96	0.04	(Majumder and Kaviraj, 2015)
Cypermethrin	*Pila globosa*	96	545	(Majumder and Kaviraj, 2015)
Cypermethrin	*Katelysia opima*	96	2750	(Mukadam and Kulkarni, 2014)
Cypermethrin	*Lamellidens marginalis*	96	20300	(Kumar *et al.*, 2012)
Cypermethrin	*Brachionus plicatilis*—larvae	24	300	(Sánchez-Fortún and Barahona, 2005)
Cypermethrin	*Brachionus calyciflorus*—larvae	24	80	(Sánchez-Fortún and Barahona, 2005)
Cypermethrin	*Thamnocephalus platyurus*—larvae	24	670	(Sánchez-Fortún and Barahona, 2005)
α-Cypermethrin	*Branchiura sowerbyi*	96	13.41	(Bej *et al.*, 2015)
α-Cypermethrin	*Bellamya bengalensis*	96	15	(Pal and Bej, 2019)
Esfenvalerate	*Chironomus riparius*	96	0.13	(Samsøe-Petersen *et al.*, 2001)
Fenvalerate	*Micronecta scutellaris*	96	5710	(Ambrose, 2015)
Permethrin	*Astacus leptodactylus*	96	0.903	(Günal *et al.*, 2021)
β-Cyfluthrin	*Dressienna polymorpha*	96	509.62	(Söylemez *et al.*, 2021)
γ-Cyhalothrin	*Macrobrachium nippoensis*	96	0.28	(Wang *et al.*, 2007)
λ-Cyhalothrin	*Macrobrachium nippoensis*	96	0.04	(Wang *et al.*, 2007)
λ-Cyhalothrin	*Macrobrachium rosenbergii*	96	0.066	(Bhavan *et al.*, 2015)

TABLE 9.3 Median lethal concentration LC_{50} values (μg/L) of different pyrethroids to aquatic invertebrates.—cont'd

Pyrethroid	Species	Hour	LC_{50}	Reference
λ-Cyhalothrin	*Tubifex tubifex*	96	130	(Chatterjee *et al.*, 2021)
Bifenthrin	*Branchiura sowerbyi*	96	1.043	(Saha *et al.*, 2020)

stress, mollusca oversecrete mucus and close their shells, probably to protect themselves (Ait Ayad *et al.*, 2011). Cypermethrin decreased both A and B neurosecretory cells in freshwater snails, *Lymnaea acuminata* (Borale and Ahirrao, 2013). In another study on the freshwater mussels *Unio elongatulus eucirrus*, Köprücü *et al.* (2010) reported that cypermethrin increased lipid peroxidation with a decrease in reduced glutathione and catalase activity in gills and digestive glands, inhibiting filtration by shortening active periods. Chronic pyrethroid exposure in *Lymnaea acuminate* affects oxidative metabolism in the hepatopancreas and ovotestis, as well as reproduction by increasing the number of eggs, egg mass, and high mortality rate among the offspring (Tripathi and Singh, 2004). In addition, pyrethroids reduced filtration rate and induced neural abnormalities (Khazri *et al.*, 2023).

9.7 Effects on tadpoles of Amphibia

Tadpoles of toads seemed to be more resistant to pyrethroids than crustacean zooplanktons. Table 9.4 shows (LC_{50}) values (μg/L) of different pyrethroids to amphibian tadpoles. The 96 h LC_{50} value of cypermethrin to the tadpole of *Duttaphrynus melanostictus* is 8.97 μg/L (Majumder and Kaviraj, 2015); 9.0 μg/L (Saha and Kaviraj, 2008); 3.34 μg/L (David *et al.*, 2012). The 48 h LC_{50} value of cypermethrin to tadpole larva of *Rana temporaria* is 6.5 μg/L (Paulov, 1990). The developmental stage of the exposed individuals determines an amphibian's susceptibility to a pesticide (Greulich *et al.*, 2002). The hatching success of the egg of the *R. arvalis* might be reduced by as low as 1.0 μg/L of α-cypermethrin (Greulich *et al.*, 2002). *R. arvalis* larvae that were successfully hatched had aberrant behavior, such as twisting and swimming in an atypical manner. Greulich *et al.* (2002) also noted that metamorphosis might be delayed by α-cypermethrin at even lower concentrations (0.1 mg/L). Histopathological and genotoxic effects of pyrethroids in *Pelophylax ridibundus* tadpoles were reported by Alnoaimi *et al.* (2021). Deltamethrin and cypermethrin induced changes in the oral morphology of *Physalaemus gracilis* tadpoles (Vanzetto *et al.*, 2019).

9.8 Effects on freshwater fish

Fish serve crucial roles in the aquatic food web, nutrient recycling, productivity, and high sensitivity to pollutants, all of which make them indispensable components of aquatic ecosystems (Yancheva *et al.*, 2015). Since fish are a major source

TABLE 9.4 Median lethal concentration (LC_{50}) values (μg/L) of pyrethroids to amphibian tadpole.

Pyrethroid	Species	Hour	LC_{50}	Reference
Cypermethrin	*Duttaphrynus melanostictus* tadpoles	96	8.97	(Majumder and Kaviraj, 2015)
Deltamethrin	*Xenopus laevis* tadpoles	168	6.26	(Aydin-Sinan *et al.*, 2012)
λ-Cyhalothrin	*Xenopus laevis* tadpoles	168	3.94	(Aydin-Sinan *et al.*, 2012)
Deltamethrin	*Rhinella arenarum* tadpoles	48	0.00125	(Lajmanovich *et al.*, 2018)
α-Cypermethrin	*Bufotes variabilis* tadpoles	96	15.62	(Gürkan *et al.*, 2016)
Cypermethrin	*Hypsiboas pulchellus* tadpole	24	479.7	(Agostini *et al.*, 2010)
Cypermethrin	*Rhinella arenarum* tadpoles	96	11200	(Svartz and Perez-Coll, 2013)
Cypermethrin	*Bufo arenarum* tadpole	96	110	(Casco *et al.*, 2006)
Cypermethrin	*Duttaphrynus melanostictus* tadpoles	96	3.34	(David *et al.*, 2012)

of protein, omega-3 polyunsaturated fatty acids, and other micronutrients for people (Mohanty *et al.*, 2019), it is urgent to keep an eye on contaminant levels to guarantee food safety. Pesticides are the most common agrochemicals that contaminate aquatic environments (Rohani, 2023). Pyrethroids are highly toxic to fish due to their lipophilicity, which attracts them to the non-water-soluble components of gill cells and causes them to be strongly absorbed, even at low concentrations. Again, carboxylesterases that can detoxify pyrethroids are present in fish at a low level.

In consequence, metabolism and elimination of pyrethroids in fish occur more slowly than in birds and mammals (Yang *et al.*, 2020). Most of the reports revealed that pyrethroid is highly toxic to fish, and the LC_{50} values of different pyrethroids for many species of fish are found at the microgram level. There are several reports of the acute toxicity of pyrethroid to fish (Table 9.5). The toxicity of pyrethroids differs with respect to their chemical properties, such as stereoisomeric form, solubility, and formulation, as well as size, sex, developmental stage, and species concern. Technical grade α-cypermethrin

TABLE 9.5 Median lethal concentration (LC_{50}) values (μg/L) of different pyrethroids to fish.

Pyrethroid	Species	Hour	LC_{50}	Reference
Bifenthrin	*Heteropneustes fossilis*	96	3.40	(Saha *et al.*, 2021)
Bifenthrin	*Clarias batrachus*	96	3.46	(Saha and Saha, 2021)
Bifenthrin	*Oreochromis mossambicus*	96	2.42	(Saha *et al.*, 2020)
Bifenthrin	*Cyprinus carpio*	96	57.5	(Velisek *et al.*, 2009)
λ-Cyhalothrin	*Sarotherodon melanotheron*	96	9000	(Alalibo *et al.*, 2019)
λ-Cyhalothrin	*Cyprinus carpio*	96	1.48	(Chatterjee *et al.*, 2021)
λ-Cyhalothrin	*Poecilia reticulata*	96	81.83	(Salako *et al.*, 2020)
λ-Cyhalothrin	*Clarias batrachus*	96	5.0	(Kumar *et al.*, 2011)
λ-Cyhalothrin	*Oreochromis niloticus*	24	15	(Amin *et al.*, 2020)
Bifenthrin	*Brachydanio rerio*	96	3.2	(Zhang *et al.*, 2010)
Deltamethrin	*Poecilia reticulata*	96	31.51	(Salako *et al.*, 2020)
Deltamethrin	*Oreochromis mossambicus*	96	8.639	(Chukwuka *et al.*, 2022)
Deltamethrin	*Clarias gariepinus*	96	40010	(Datta and Kaviraj, 2003)
Deltamethrin	*Oreochromis niloticus*	96	15.47	(Boateng *et al.*, 2006)
Deltamethrin	*Anabas testudineus*	96	70	(Sapana Devi and Gupta, 2014)
Deltamethrin	*Danio rario*	96	0.043	(Sharma and Ansari, 2010)
Fenvalerate	*Clarias batrachus*	96	1.35	(Datta and Kaviraj, 2011)
Fenvalerate	*Channa punctatus*	96	1.0	(Datta and Kaviraj, 2011)
Fenvalerate	*Heteropneustes fossilis*	96	0.65	(Datta and Kaviraj, 2011)
Fenvalerate	*Catla catla*	96	5.0	(Tandon *et al.*, 2005)
Fenvalerate	*Cyprinus carpio*	96	3.059	(Raja *et al.*, 2010)
Permethrin	*Brachydanio rerio*	96	2.5	(Zhang *et al.*, 2010)
Permethrin	*Poecilia reticulata*	48	245.7	(Başer *et al.*, 2003)
Permethrin	*Cyprinus carpio*	96	56890	(Davoodi and Abdi, 2012)
Permethrin	*Anabas testudineus*	96	930	(Sapana Devi and Gupta, 2014)
α-Cypermethrin	*Cyprinus carpio*	96	11.03	(Bej *et al.*, 2021)
Cypermethrin	*Oreochromis niloticus*	96	4.85	(Majumder and Kaviraj, 2017)
Cypermethrin	*Labeo rohita*	96	2.27	(Majumder *et al.*, 2018)
Cypermethrin	*Mystus vittatus*	96	3.14	(Majumder *et al.*, 2018)
Cypermethrin	*Cyprinus carpio*	96	2.6	(Saha and Kaviraj, 2008)

TABLE 9.5 Median lethal concentration (LC_{50}) values (μg/L) of different pyrethroids to fish.—cont'd

Pyrethroid	Species	Hour	LC_{50}	Reference
Cypermethrin	*Cyprinus carpio*	96	0.85	(Soltanian and Fereidouni, 2017)
Cypermethrin	*Heteropneustes fossilis*	96	0.67	(Saha and Kaviraj, 2003)
Cypermethrin	*Poecilia reticulata*	96	27.07	(Salako *et al.*, 2020)
Cypermethrin	*Catla catla*	96	4.43	(Vani *et al.*, 2012)
Cypermethrin	*Cyprinus carpio*	96	3.31	(Neelima *et al.*, 2015)
Cypermethrin	*Clarias batrachus*	96	12.09	(Kumar *et al.*, 2009)
Cypermethrin	*Labeo rohita*	96	4.00	(Marigoudar *et al.*, 2013)
Cypermethrin	*Cirrhinus mrigala*	96	5.00	(Prashanth and Neelagund, 2008)
Cypermethrin	*Mystus cavasius*	72	6.12	(Ali *et al.*, 2018)
Cypermethrin	*Cirrhinus mrigala*	96	5.13	(Prashanth and Neelagund, 2008)
Cypermethrin	*Hypophthalmicthys molitrix*	96	0.917	(Shaluei *et al.*, 2012)
Cypermethrin	*Oncorhynchus mykiss*	96	31.4	(Velisek *et al.*, 2006)
Cypermethrin	*Heterobranchus bidorsalis*	96	36	(Olufayo and Alade, 2012)
Cypermethrin	*Channa striatus*	96	380.2	(Osman *et al.*, 2013)
Cypermethrin	*Clarias gariepinus*	96	63	(Ayoola and Ajani, 2008)

(98%) exerted more toxicity than technical grade β-cypermethrin (99%) to *Poecilia reticulata* (Polat *et al.*, 2002). A pesticide's solubility has a role in part of its toxicity. Fish are said to be more sensitive to acetone-soluble cypermethrin and fenvalerate than to their aqueous counterparts (Saha and Kaviraj, 2003). The technical grade of pyrethroid cypermethrin is less toxic to fish than the emulsifiable concentrate (Majumder and Kaviraj, 2015, 2017; Majumder *et al.*, 2018). *P. reticulata* juveniles were most susceptible to alphamethrin, followed by males, females, and a mixed population (Wast *et al.*, 2014). Aydin-Sinan *et al.* (2012) showed that cypermethrin is toxic to both embryos (48 h LC_{50}: 0.909 μg/L) and larvae (48 h LC_{50}: 0.809 μg/L) of *Cyprinus carpio*. Even a concentration of 0.0001 μg/L can affect embryo hatching success.

Pesticides have chronic effects that develop over time. Long-term exposure to sub-lethal doses can result in chronic effects. Fish responses to environmental stress are often assessed using a variety of biomarkers from various biological levels of the organizational and biological activities (Yancheva *et al.*, 2015). A possible mode of action of pyrethroid on fish physiology and metabolic pathways has been depicted in Figure 9.2. The effects of pyrethroids on different biomarkers in fish have been described here.

9.8.1 Effects on behavioral biomarkers

Pyrethroid-exposed fish showed flaring of opercula, restlessness, erratic and darting swimming patterns, and profuse mucous secretion (Chatterjee *et al.*, 2021; Majumder and Kaviraj, 2017). Lateral swimming and loss of equilibrium are likely symptoms of neurological impairment induced by pyrethroid through its action on voltage-gated sodium channels and disturbances in nerve impulse propagation.

9.8.2 Effects on hematological biomarkers

In routine toxicological studies, the most frequently used blood parameters are the total count of RBC (red blood corpuscle), WBC (white blood corpuscle), hemoglobin (Hb%), and hematocrit contents (Rohani, 2023). Several studies reported a decrease in RBC count and Hb% in different fish species exposed to different pyrethroids (Chatterjee *et al.*, 2021; Majumder and Kaviraj, 2017), which indicated anemia and a hypoxic state (Bej *et al.*, 2021), probably due to adverse effects of pyrethroids on erythropoiesis and hemolysis (Rohani, 2023). A significant increase in the WBC count of fish species as an outcome of pyrethroid assault indicated hypersensitivity of leucocytes to pyrethroids, and these changes

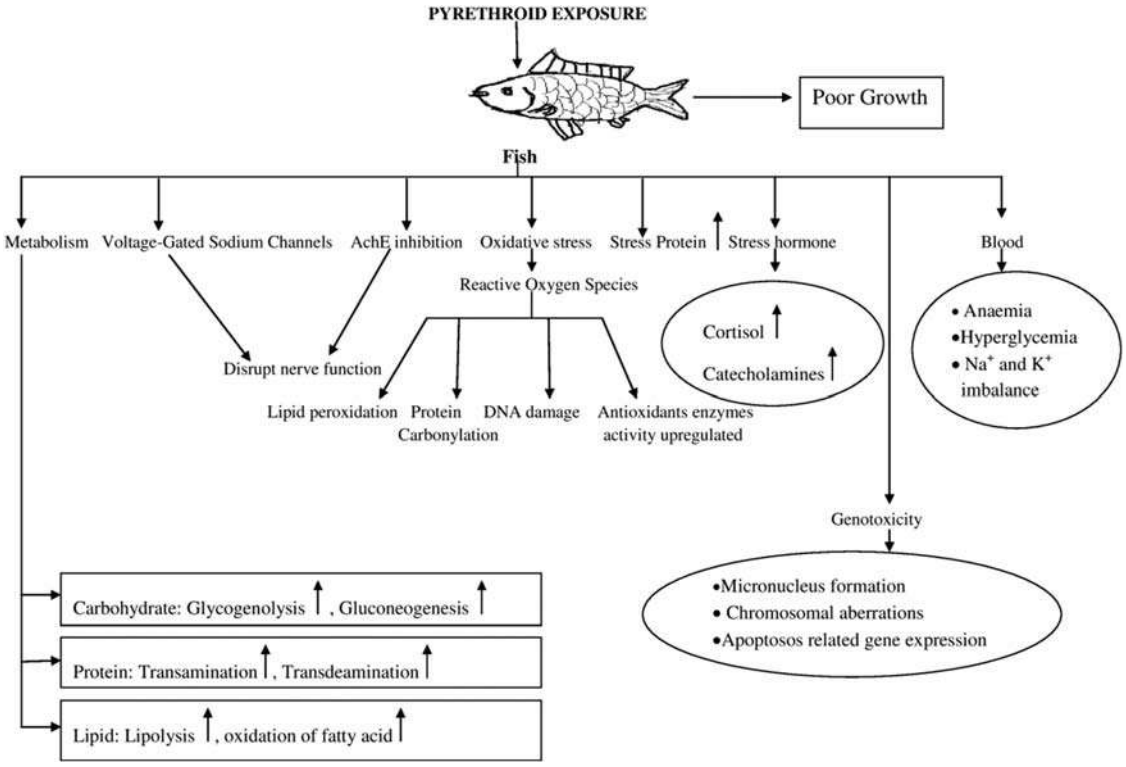


FIGURE 9.2 Effects of pyrethroids on fish physiology and biochemistry. The effects of pyrethroids on different biomarkers in fish.

may be due to immunological reactions that produce antibodies to cope with stress (Majumder and Kaviraj, 2017). Stress-related hyperglycemia is another finding reported in many fish species exposed to pyrethroid (Chatterjee *et al.*, 2021).

9.8.3 Effects on biochemical biomarkers

Pyrethroids are potent neurotoxicants and can induce severe biochemical and physiological changes in fish. λ-Cyhalothrin causes an increase in plasma glucose, cholesterol, creatinine, alkaline phosphatase (ALP), and transaminase (AST and ALT) levels and a decrease in total protein and albumin in the blood of *C. carpio* (Chatterjee *et al.*, 2021). A rise in plasma glucose level and a simultaneous decline in liver glycogen level are common occurrences in fish under stress (Majumder and Kaviraj, 2017). Transaminases serve to supply energy during their role as a strategic link between protein and carbohydrate metabolisms under stress; in consequence, their activity gets changed (Youssef, 2017). A rise in acid phosphatase activity (ACP) in cypermethrin-exposed fish indicates liver injury (Majumder and Kaviraj, 2017). An increase in lactate dehydrogenase (LDH) activity and a fall in succinate dehydrogenase (SDH) and malate dehydrogenase activity during deltamethrin-induced stress in fish were reported by Mohan *et al.* (2017). Acetylcholinesterase inhibition was reported in fish due to exposure to λ-cyhalothrin (Chatterjee *et al.*, 2021), cypermethrin (Majumder and Kaviraj, 2015, 2017), and deltamethrin (Zhang *et al.*, 2017). Suvetha *et al.* (2010) reported electrolyte imbalance in the blood of cypermethrin-intoxicated *C. carpio*, where sodium ion (Na^+), potassium ion (K^+), and chloride ion (Cl^-) levels fell below normal, and the activity of Na^+/K^+ ATPase was inhibited. Pyrethroids can act as endocrine disruptors in fish (Eni *et al.*, 2019). Permethrin-induced rise in adrenocorticotrophic hormone (ACTH) and cortisol levels was reported in *C. carpio* (Erdoğan *et al.*, 2022). Furthermore, the liver of λ-cyhalothrin-exposed fish showed upregulation of heat shock protein (*HSP70*) and downregulation of cytochrome P450 1A (*CYP 1A*), as reported by Khalil *et al.* (2020).

9.8.4 Effects on histopathological biomarkers

Pyrethroids are mostly lipophilic and enter the fish's body mostly through the skin, gills, or mouth, and from there they get distributed into different body parts (Rohani, 2023). Their effects in fish can be interpreted through the analysis of histopathological lesions in major organs in the form of epithelial hyperplasia on secondary gill filaments and necrosis on primary gill lamellae, vacuolation, and necrosis in hepatic tissues; glomerular shrinkage, thickening of Bowman's capsule,

and degeneration of the epithelial layer of renal tubules in kidney tissues (Majumder and Kaviraj, 2022); mononuclear infiltration, neuronal degeneration, and severe pycnosis in the brain tissues (Ayoola and Ajani, 2008); condensation of spermatogenic cells, vacuolization in the tubular epithelium, and disruption of interstitial cells of testes; shrinkage and micronucleus within the red blood cells (Saha and Kaviraj, 2017); damaged lepidonts on scales (Babu *et al.*, 2014); splitting and degeneration of muscle fiber including vacuolar degeneration in skeletal muscle (Singh *et al.*, 2021); and necrosis and infiltration of mononuclear leucocytes and eosinophils toward the lamina propria in the intestinal tissues (Cengiz and Unlu, 2006).

9.8.5 Effects on oxidative stress biomarkers

Oxidative stress is one of the adverse outcomes in fish suffering stress due to λ-cyhalothrin (Chatterjee *et al.*, 2021), deltamethrin (Elia *et al.*, 2017), and cypermethrin. It generates excess reactive oxygen species (ROS) that can induce lipid peroxidation, protein carbonylation, and damage to DNA (Nedzvetsky *et al.*, 2021). Few recent studies reported that during pyrethroid stress in fish, catalase activity falls, hydrogen peroxide accumulates, and superoxide dismutase activity falls (Chatterjee *et al.*, 2021). In consequence, malondialdehyde (MDA) levels increased (Adeyemi *et al.*, 2014). Yang *et al.* (2020) reported a fall in antioxidant enzyme activity in fish under pyrethroid stress.

9.8.6 Effects on physiological biomarkers

Chronic pyrethroid exposure can reduce the growth and survival of fish, as already documented in several fish species by different workers (Majumder and Kaviraj, 2017). In addition, both the protein and lipid contents are much lower in such fish, probably to supply extra energy to withstand the stress through protein catabolism and inhibition of lipid synthesis (Abdel-Rahman Mohamed *et al.*, 2021).

9.8.7 Effects on cytological and genotoxic biomarkers

Cypermethrin-induced micronucleus formation in RBC was reported by Saha and Kaviraj (2017). Synthetic pyrethroid λ-cyhalothrin upregulates the expression of replicative protein A (RPA1), which is essential in DNA replication as well as repair in the brain of *Oncorhynchus mykiss* (Nedzvetsky *et al.*, 2021). Jin *et al.* (2011) reported that cypermethrin increased the expression of a number of apoptosis-related genes, including p53, Apaf1, and Cas3, and decreased the Bcl2/Bax expression ratio. In embryo-larval stages of zebrafish, cypermethrin caused changes in gene expression in terms of downregulation of *ogg1* (codes for 8-oxoguanine DNA glycosylase1 protein), increase in p53 gene expression and caspase-3 activity, notable apoptotic signs in the nervous system, morphological abnormalities, and induction of anti-oxidative enzyme levels (Shi *et al.*, 2011).

9.8.8 Effects on immunological biomarkers

In fish, pyrethroid-induced toxicity is also reflected in a number of immunological parameters. Narra (2016) recorded a higher leukocyte count in addition to a fall in albumin, globulins, and lysozyme activity in cypermethrin-intoxicated fish, whereas λ-cyhalothrin stress lowered the activity of the antioxidant enzymes superoxide dismutase and glutathione peroxidase; as a consequence, levels of 8-hydroxyl-2-deoxyguanosine (8-OHdG) increased as a possible outcome of DNA damage. It also depressed growth and immune functions and upregulated expressions of interleukin and chemokine (Abdel-Rahman Mohamed *et al.*, 2021). Arslan *et al.* (2017) pointed out the fact that cypermethrin affected organ structure and functions, mainly in the brain. The immunopositive response of 8-hydroxyl-2-deoxyguanosine (8-OHdG) in both the nuclei and cytoplasm of neurons, inducible nitric oxide synthetase (iNOS) in the cytoplasm of neurons, as well as glial cells, and upregulation of caspase 3, caspase 8, iNOS, and metallothionein 1 (MT1) genes, substantiated the fact in fish.

9.8.9 Effects on reproductive biomarkers

In fish, pyrethroid exposure can affect sperm quality (Kutluyer *et al.*, 2016), ovarian maturation (Sarkar *et al.*, 2014), and breeding success, where the total number and amount of eggs, percentage of fertilization, expected number of eggs getting fertilized, and hatching success all may decrease even with short-term exposure (Adhikari *et al.*, 2006). Cypermethrin, even at a concentration of 2 μg/L, can lower hatching success and cause embryonic and larval malformations in *Mystus cavasius* (Ali *et al.*, 2018). While studying the effects of pyrethroid on salmon milt and eggs by Moore and Waring (2001), it was found that the number of fertilized eggs decreased as it affected the priming effect of males to respond. In addition, pyrethroid stress in fish in the pre-spawning phase can lower the levels of 17β-estradiol and 11-ketotestosterone within the plasma of their bodies (Singh and Singh, 2008). In *Odontesthes bonariensis,* an in vitro study of pyrethroid exposure found

an antiestrogenic effect. In contrast, no effects on sex ratio, gonadal development, or germ cell production were recorded during the in vivo study (Carriquiriborde *et al.*, 2007).

9.8.10 Effects on omics biomarkers

The application of "omics," which includes genomics, transcriptomics, proteomics, lipidomics, and metabolomics, is now growing for a better understanding of contaminants in stress ecology and aquatic toxicology as well (Ebner, 2021). Its application to understand pesticide-imposed stress on different aquatic animals is increasing. Biales *et al.* (2011) showed that a single or mixture of permethrin and terbufos are capable of inducing a proteomic response in the brains of fathead minnows. Determining which proteins exhibit differential expression could be helpful in comprehending how binary mixtures work. In another study, chronic exposure to deltamethrin affected lipid metabolism, disrupted endocrine functions, and instigated pro-inflammation in crucian carp, as revealed by transcriptomics analysis, and further analysis of integrated transcriptomics and metabolomics unveiled that biosynthesis of steroid hormone and metabolism of arachidonic acid were the two crucial processes in the brain (Wu *et al.*, 2024).

9.9 Future research scopes

A few information gaps have been found for future research while making a thorough analysis of available literature dealing with the harmful effects of pyrethroids on freshwater invertebrates and fish. The majority of studies in pesticide research now center on freshwater fish. Our understanding of species-specific fish sensitivity to pesticides under varied ambient environmental factors may be furthered by additional studies investigating the impact of pesticides on cold-water fish as well as marine fish. Even though much research has already reported the acute toxicity of pesticides on many other non-target aquatic organisms, not many in-depth, long-term studies have yet been carried out on them. Special emphasis should be given to examining the impacts of inert components or adjuvants in pesticide formulation and their effects on non-target organisms. Designing a low-cost and accurate strategy is the present need for a fast and precise understanding of pesticide-mediated risk to non-target organisms, fish in particular, that may indirectly pose a threat to human health. The article threw light on the importance of introducing, explaining, and concluding a certain study dealing with the effects of pyrethroids on fish for an indirect understanding of agrochemical contamination. Although the use of pesticides cannot be avoided, steps should be taken to maintain aquatic resources and water quality. A few of the thrust areas that may offer future research directions include the generation of target-specific, environmentally friendly pesticide formulations, multi-biomarker-based bioassays, and the preparation of fish feed with natural ameliorative agents to combat pesticide stress and adverse outcome pathway (AOP) network development.

9.10 Conclusion

The chapter presents literature on pyrethroids covering a range of topics, including the evolution of pyrethroid generation, their multifaceted applications, environmental fate, mechanism of action, and harmful effects on fish, amphibian tadpoles, and freshwater invertebrates. Pyrethroids are very harmful to aquatic organisms, even at low concentrations of 1 μg/L. Zooplanktons, aquatic insects, and fish are more likely to be affected than mollusks and oligochaete worms. In fish, pyrethroids have negative effects on the metabolic pathway, nerve impulse propagation, histopathology of several organs, and behavior. The evaluation of multiple biomarkers in pyrethroid-exposed fish offered authentic information on fish health and their stress responses. There is a need to be cautious when using pyrethroids in the agriculture field and to adopt integrated pest management practices.

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Chapter 10

The ecological toll: Biodiversity loss and habitat degradation caused by agricultural waste

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Chapter Outline

10.1. Introduction 155
10.2. Various sources of agricultural waste 156
10.3. Impact of agricultural waste on ecosystem 160
10.4. Soil faunal diversity and soil degradation 162
10.5. Impact of agricultural residue burning on biodiversity 162
10.6. Impact of agriculture waste on greenhouse gas emission 163
10.7. Policy implications and knowledge gaps 163
10.8. Sustainable approaches for agricultural waste management 163
10.9. Conclusion 164
Acknowledgments 164
References 164

10.1 Introduction

The world's population has increased from 3.7 billion people in 1970 to 7.9 billion people in 2021. By 2050, it is expected to reach 9 billion, and by 2100, it will reach 11 billion. Therefore, ensuring food security will become a difficult task in the future. Crop and livestock output has increased significantly to meet the high demands of ever-increasing populations, which has further increased the amount of agricultural waste produced (Koul, Yakoob, and Shah, 2022). In recent times, the amount of agricultural waste has increased worldwide, raising more attention to the adverse impacts of environmental degradation. This waste comprises remnants from agricultural practices, byproducts from food processing, and so on. The agricultural biomass exhibited a greater ash content than woody biomass, which in turn impacted the Minimum Explosible Concentration (MEC) (Xue *et al.*, 2016). Livestock raising creates numerous types of waste comprising solid outputs such as manure, liquid waste from sanitation methods, and air pollutants such as hydrogen sulfide and methane (Obi *et al.*, 2016). Untreated or improperly recycled agricultural waste causes worldwide environmental pollution and extensive eutrophication of water bodies such as rivers, lakes, streams, and oceans (He *et al.*, 2016). Air pollution from agricultural waste is caused by emissions from agricultural machinery and the widespread practice of open burning; particularly in developing nations, chemical fertilizers are essential for boosting agricultural yields but lead to the contamination of water bodies and groundwater, which is the main cause of eutrophication. The eutrophication is caused by nutrient runoff, especially phosphorus, which causes an unpleasant taste and odor in public water sources, an abundance of algae, and low

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oxygen levels, which causes fish mortality. Using fertilizers, particularly on frozen ground, raises the concentration of metals, nitrogen, phosphorus, and pathogens in receiving streams and rivers, exacerbating eutrophication and increasing the danger of contamination (Nagendran, 2011). Methane and nitrous oxide are the two main greenhouse gases (GHGs) emitted from agricultural wastes, and their emissions have a major influence on climate change. Agriculture emissions are diverse, with the burning of biomass and emissions from animals being major contributions. Food waste disposal contributes to environmental degradation through inefficient use of water, land, energy, and other resources, in addition to signifying the waste of valuable resources (Dudley and Alexander, 2017). Recycling agricultural waste has been recognized as a potential strategy to mitigate carbon emissions such as reusing crop straws to reduce methane emissions. Based on the Environmental Protection Agency (EPA) 2018 wasted food report, the United States generates approximately 93.4 million tons of food waste annually, equivalent to roughly 285.8 kilograms per capita. It has been found that the production of food waste has consistently risen over the past five decades (Chen *et al.*, 2022). Researchers are focusing on managing the production of food waste to reduce risks to the environment and turn waste into beneficial resources. Vermicomposting, biomethanation, and taking the circular economy into account are some strategies. Agriculture benefits from the application of nanotechnology, especially in the production of nano-pesticides and fertilizers that help to manage plant diseases and release agrochemicals under regulated conditions. Utilizing nano-adsorbents and transforming waste into useful nanomaterials are two aspects of the nano-management of agricultural wastes (Hossain, Shahrukh, and Hossain, 2022). It is necessary to enforce laws and regulations that promote reduction, reuse, regeneration, and recycling of waste in order to eventually move the production sector in the direction of zero waste. It is necessary to develop new legislation and use creative waste management techniques that promote recycling waste and turning it into useful resources. The efficient handling and application of agricultural waste can provide avenues for value additions, thus making a contribution to ecological sustainability and energy security (Awogbemi and Kallon, 2022).

10.2 Various sources of agricultural waste

Improper processing or disposal of agricultural waste can have negative effects on human health and environmental degradation. If agriculture waste is not treated or disposed properly, it spreads diseases and contaminates soil as well as groundwater (Mieldažys *et al.*, 2016). Agricultural advances often result in waste development due to intensive agricultural methods and excessive chemical use, which impacts local and global ecosystems. This waste might have different quantities and qualities depending on certain farming techniques. It includes things like overuse of fertilizers, empty pesticide bottles that contaminate the environment, animal waste that contaminates the water, as well as air and aquaculture waste that comes mostly from feed consumption (Figure 10.1). All these factors cause serious risks to the environment as well as biological resources (Damalas, Telidis, and Thanos, 2008).

- Fertilizers and pesticides
- Organic wastes
- Genetically modified organisms (GMOs)
- Agro-industrial waste

10.2.1 Fertilizer and pesticides

Fertilizer industries are the chief source of the high level of pollutants that result in environmental degradation. For example, the large amount of phosphogypsum produced requires high management costs and presents a major disposal difficulty. Pesticides are converted into gases through volatilization, which negatively impacts biodiversity. Pesticide volatilization can create "drift," which affects livestock, creatures, and surrounding crops (Mahmoud and Loutfy, 2012). The extensive use of pesticides in agricultural and pest control activities exacerbates the serious threats to human health and the ecology due to improper treatment of pesticide waste. Pesticide residues are left behind in urban and rural environments, including leftover pesticides, excess solutions, contaminated water, and abandoned containers. This is mainly due to a lack of understanding of proper waste disposal techniques. Pesticide-contaminated water puts non-target creatures in danger, and its unintentional discharge into the environment may harm ecosystems. Inadequate control of pesticide residues and containers remains a major obstacle to proper waste disposal procedures, even with awareness campaigns (Damalas, Telidis, and Thanos, 2008).

Fertilizers are essential for raising agricultural production and farmer incomes. The main products that govern the fertilizer market include urea, diammonium phosphate (DAP), muriate of potash (MoP), single superphosphate (SSP), ammonium sulfate (AS), ammonium chloride (AC), and nitrogen phosphorus (NP)/nitrogen phosphorus potassium (NPK).

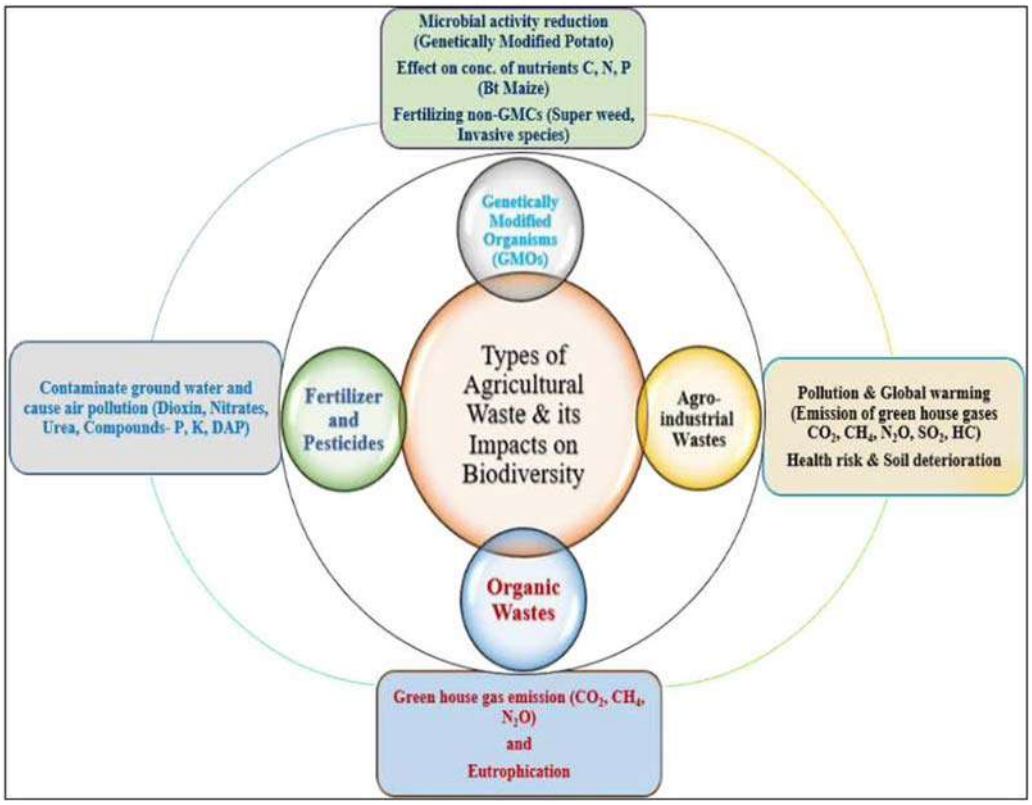


FIGURE 10.1 **Types of agricultural waste based on various sources.** Agriculture waste is primarily divided into four categories: fertilizers and pesticides, organic wastes, genetically modified organisms (GMOs), and agro-industrial waste.

The use of pesticides and fertilizers seriously harms the ecosystem to a greater extent. There is a possibility of air pollution and contaminated groundwater associated with increased levels of residual nitrates and harmful substances in the soil (Rahman and Zhang, 2018). Numerous biocidal chemicals exhibit high reactivity. Due to their inherent properties and usage patterns, they can be extremely hazardous if not used properly. Hazardous biocides used improperly can particularly threaten vulnerable groups, including children and expecting mothers (Mahmoud and Loutfy, 2012).

Production of fertilizers and pesticides to satisfy the demands of agriculture sector largely contributes to environmental degradation (Walling and Vaneeckhaute, 2020). Fertilizers are classified into different categories: chemical fertilizers, inorganic fertilizers, organic matter fertilizers, and organomineral fertilizers. The two primary categories of chemical fertilizers are liquid and solid. Solid or liquid fertilizers include primary single and complex nutrients for crops including potassium (K), phosphate (PO_4), and nitrogen (N) fertilizers. They also include compound fertilizers such as NPK, NP, NK, and PK fertilizers. Liquid inorganic fertilizers include either single or complex nutrients. Furthermore, there are micronutrient fertilizers that include elements such as molybdenum, iron, zinc, copper, manganese, boron, and cobalt as well as secondary nutrients containing inorganic fertilizers. Organic matter fertilizers include plant- and animal-based varieties such as farmyard manure, chicken manure, bat dung, and microbial fertilizers. They can also be in liquid or solid form. Organomineral fertilizers combine chemical and organic ingredients to provide a range of nutrient formulations, including N, NP, NK, and NPK, occasionally with the addition of enzymes. The environment is damaged due to the excessive use of fertilizers, particularly nitrogenous based. Ultimately, overfertilization also affects people because toxic elements enter the food chain through bioaccumulation. Soil comprises gas, water, microbes, minerals, and soil organic matter. Naturally occurring heavy metals such as chromium, cadmium, mercury, lead, and arsenic are found in soil naturally due to factors like the weathering of parental rocks (Alloway, 2013). Toxin poisoning of the soil might result from commercial phosphate fertilizers containing traces of heavy metals. Applying fertilizers randomly can lead to soil segregation, which can affect crop quality and produce an uneven distribution of nutrients (Alengebawy *et al.*, 2021). Maintaining soil quality is crucial for the future agricultural sector regarding water retention, carbon sequestration, crop yield, and waste management (Khan *et al.*, 2018). The condition of soil is affected by activities such as chemical, physical, and biological processes. For example, Cu availability in soil can acidify the soil, which alters the balance of minerals and

can be harmful. Low pH levels increase the mobility and availability of heavy metals (HMs) in soil, posing a risk to food crops and human health (Rehman *et al.*, 2023). There are several factors that impact the biological health of soil, including soil respiration, faunal diversity, nitrogen mineralization, waste breakdown, variety of microorganisms, and nutrient storage capacity. Particularly crucial for the mineralization and immobilization of nutrients are bacteria and fungi. Chemical fertilizers have the potential to change microbial populations and activity, which might impact the pH and biological processes of the soil. Elevated quantities of nitrogenous fertilizers have the potential to suppress soil microorganisms, resulting in a reduction in microbial biomass and diversity, which may affect plant development. Research has indicated that the acidifying effects of various nitrogenous fertilizers are varied, resulting in distinct impacts on soil pH and nutrient availability. The availability of several cations rises and decreases with decreasing soil pH, changing the fertility of the soil (Tyagi, Ahmad, and Malik, 2022).

Insecticides belong to several groups. The most prevalent of them are organochlorines, with α-endosulfan and β-endosulfan standing out as the main examples. Among carbamates, methamidophos is the most commonly found, and methomyl is the most prominent comparatively. Among the pyrethroid class, permethrin is the principal pesticide (Kaur *et al.*, 2019). Pesticides often contaminate surface waterways such as lakes, ponds, and streams, endangering fish and other species that are not intended targets. These substances are poisonous and can cause other worse stresses such as dangerous algal blooms, which can lower fish populations. Pesticides are ingested by aquatic creatures through their gills and skin and pollute the water (Riaz *et al.*, 2021). Organophosphorus pesticides block cholinesterase and continuously accumulate acetylcholine at synapses, posing a serious threat to both vertebrates and invertebrates. This blockage of nerve impulse transmission results in rapid muscular spasms, paralysis, and finally death (Kaur *et al.*, 2019). Herbicides kill aquatic plants, lowering oxygen levels, suffocating fish, and decreasing their output. Because of runoff and spray dispersion, surface waterways frequently contain greater pesticide amounts than groundwater. Amphibians are severely harmed by pesticides such as atrazine, chlorpyrifos, glyphosate, malathion, carbaryl, and endosulfan, which affect their immune systems, raise death rates, and interfere with reproduction. Exposure to pesticides harms animals and terrestrial plants. Herbicide drift has the potential to damage adjacent trees and shrubs, and glyphosate lowers seed quality while rendering plants more susceptible to disease. Neonicotinoids negatively affect the health and behavior of beneficial insects such as bees, causing their populations to decline due to pesticide use. Pesticides have decreased bird numbers, causing fatalities and alterations in behavior. Pesticides kill soil bacteria that are vital to soil fertility and nutrient cycling, especially those that fix nitrogen. Pesticides affect earthworms and other creatures by generating neurotoxic effects and DNA damage, while herbicides destroy symbiotic fungi that are essential for plants to absorb nutrients (Mahmood *et al.*, 2016).

10.2.2 Organic waste

Annually, 700 million tons of organic waste are generated, which poses challenges for appropriate disposal and frequently results in inadequate dumping techniques and burning practices. Organic wastes such as food scraps, manure, sugarcane bagasse, wheat straws, vegetables, crop stalks, jute fibers, and various other materials are rising annually (Kannan and Kallapiran, 2022). Fruit and vegetable residues include leftovers from apricots, almonds, apples, and other fruits and vegetables, whereas crop residues are materials such as straws, husks, or stubble from other crops. Different processing industries produce different types of wastes: for example, processing apples produces pomace, and processing mangos produces peels and kernels (Ajila *et al.*, 2012). A huge amount of organic waste is produced annually, mostly from food and green sources. Out of waste generated, around 42% is recovered using several collecting techniques. To produce high-quality compost, the separated organic components are often processed aerobically. However, a large proportion of this organic fraction still remains present in residual municipal solid waste (MSW), with around 40% of it going through mechanical and biological treatment (MBT) to stabilize its components that degrade biologically. This has resulted in environmental issues including greenhouse gas emissions and foul landfill odors. Emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and non-methane volatile organic compounds (NMVOC) occur throughout this biological stabilization process and need to be closely monitored (Buratti *et al.*, 2015). Anaerobic digestion and composting use microorganisms to break down organic waste into compost and biogas, offering environmentally friendly alternatives to landfill disposal. However, before composting or anaerobic digestion can take place, agricultural waste must first be treated due to its high lignocellulose content. Especially for lignocellulosic biomass, microbial treatments are essential to guarantee effective degradation and biogas generation (Leow *et al.*, 2018). The handling of MSW in developing nations is complicated by the significant amount of organic waste, which sometimes surpasses 70% when compared to industrialized countries. Because of its high moisture content, this composition makes waste-to-energy solutions difficult to implement, and its limited source separation makes recycling more difficult. Improper waste decomposition can lead to lakes that serve as reservoirs for public water sources developing unfavorable color, taste, and odor problems. When a large

amount of organic matter such as manure is added to a water source, it results in rapid proliferation of bacterial populations and leads to a sharp decline in dissolved oxygen levels in a stream. The fermentation of entire maize or sorghum plant byproducts produces silage leachate. Silage is a type of cattle feed that is fermented at high moisture levels and depletes surface water oxygen due to its high biological oxygen requirements. This depletion worsens during late summer and early fall when streams already have low dissolved oxygen levels due to high temperatures and low flow rates. Furthermore, silage leachate has the potential to pollute groundwater. Phosphorus (P) can accelerate the aging process of lakes and promote the growth of aquatic weeds and algae in freshwater. POPs (persistent organic pollutants) are hazardous chemicals that stay in the environment and do not decompose, affecting human health in addition to biodiversity. They accumulate in organisms and spread through water, air, and migratory species, eventually concentrating in both aquatic and terrestrial environments.

10.2.3 Agro-industrial wastes

Agro-industrial waste includes a wide range of categories including agricultural residues, food processing residues, energy crop residues, and leftovers from the manufacturing of biofuels. It accounts for around 15% of all garbage produced in any country. The techniques and equipment used for collection, handling, and processing are dependent on the kind of waste, which is divided into different categories such as crop waste, fruit/vegetable waste, grain/legume waste, and distillery/brewery waste. Certain wastes are produced by other sectors, *e.g.,* the starch business creates tapioca waste, and the rice milling industry produces rice husk. Bagasse, molasses, grape pomace, and yeast sludges are produced by the wine and sugarcane industries. Most brewer's waste comes from discarded grain. Organic substances such as polysaccharides, proteins, sugars, lipids, acids, starch, vitamins, minerals, and fibers are abundant in agro-industrial waste. Lignocellulose is a common organic component found in most agro-wastes. It is made up of cellulose, hemicelluloses, and lignin. Approximately 500 million tons of agricultural residue are generated worldwide each year. Of this amount, 18.4%, or 92 million tons, is burned in India, contributing to pollution and global warming by producing harmful gases. The issue of untreated agro-industrial waste being released into land and water bodies is a serious threat to the ecosystem. Certain wastes include dangerous substances that can harm ecosystems by contaminating the air, water, and soil. Untreated agricultural and industrial waste can damage soil microorganisms, cause eutrophication, release hazardous bacteria and pesticide residues, and cause infectious illnesses. In addition to greenhouse gases like methane and nitrous oxide, uncontrolled combustion releases toxic compounds such as nitrogen oxides, sulfur dioxide, inhaled fine particles, cancer-causing dioxins, furans, and polycyclic aromatic hydrocarbons. It has adverse effects on human health and greatly adds to smog and climate change. Moreover, the organic and inorganic materials in these wastes damage aquatic ecosystems and cause cancer, hormone imbalances, and genetic abnormalities (Singh *et al.*, 2021). Agro-industrial waste causes severe problems, especially in areas where waste output is high. Significant amounts of solid organic waste and wastewater can cause a variety of environmental and health problems if they are not properly disposed. Tequila is an alcoholic beverage that is fermented and made solely from *Agave tequilana*. In the tequila production process, four main steps are used: fermentation, distillation, aging, and bottling. *Agave* is processed to extract sugar. If vinasses are not properly handled, they can provide significant environmental problems because of increased levels of total solids (TS), acidity, chemical oxygen demand (COD), and phenolic chemicals. Untreated vinasses can accumulate in soil and water and release disagreeable odors when organic matter decomposes, increasing the possibility of environmental damage from improper disposal. Proper discharge of vinasses costs a lot of money. Therefore, vinasses are frequently disposed of. This causes eutrophication of neighboring water bodies, soil deterioration, and possible health risks for the local population. Furthermore, compared to other industries, the tequila business generates higher amounts of agro-industrial waste, which causes a substantial negative impact on the environment. Because of the elevated ion levels in the receiving water bodies, this protracted condition may result in soil deterioration, the transfer of heavy metals, and detrimental impacts on aquatic life.

10.2.4 Genetically modified organisms (GMOs)

Those organisms whose genetic makeup is artificially altered to modify some aspects of their features are known as genetically modified organisms (GMOs). Basically, "genetic modification" or "genetic engineering" methods allow researchers to identify specific genes that regulate certain traits, extract them from original source, and insert them straight into the cells of viruses, bacteria, plants, and animals (Prakash *et al.*, 2011). The transmission of genetic material from one to another species was first identified by scientists in 1944. Maize, soybean, papaya, alfalfa, etc., are the main commercialized genetically modified crops. Crops can be genetically modified to develop resistance against pests, herbicides, and drought to produce more grains and faster-growing leaves as well as plants (Jha *et al.*, 2020). However, due to the possible harm that genetically modified plants could cause to people's health and the environment, the introduction of transgenic

plants has remained quite contentious in many nations (Liu *et al.*, 2005). Eventually, the soil ecology is exposed to cry proteins derived from genetically modified crops. Litter eventually decomposes and releases them into the soil environment. Conventional tillage distributes these proteins at low concentrations across the topsoil, giving them opportunity to interact with a high number of microbes. The insecticidal cry protein found in Bt maize continues to function for a minimum of 180 days. Therefore, both intended and unintended soil species may be impacted. The production of concanavalin A and *Galanthus nivalis* agglutinin by genetically modified potatoes resulted in a 10% microbial activity reduction. The population of intraradical fungi was drastically reduced, and the population of bacteria increased tenfold in rice that expressed chitinase. The Cry1Ab gene in Bt maize caused the stem to have more lignin. Following degradation, such a change in crop may affect the amount of carbon, nitrogen, and phosphorus in the soil. GMCs have the ability to stop those fungi from growing that produce biofertilizers for crops. It would eventually reduce the amount of nutrients present in the soil. Pollens present an opportunity for transgenes to escape. Such pollens carry a significant risk of fertilizing non-GMCs. This could result in emergence of superweeds or a large concentration of exotic or invasive species, which would disrupt soil biodiversity and hinder the development of other species (Jha *et al.*, 2020).

10.3 Impact of agricultural waste on ecosystem

Agricultural waste such as manure and organic leftovers causes habitat degradation and biodiversity loss (Table 10.1). It absorbs water, reduces soil capacity, and increases nutrient content in water bodies, causing issues like algal blooms. Excessive waste from farms contaminates runoff, degrading the quality of water. Environmental concerns are exacerbated by dust produced by offloading poultry manure and the unpleasant odor of waste storage. Olive oil mill wastewater (OMW) with a high phenol and organic content dumped into water bodies can degrade water and soil, disturbing ecosystems (Komnitsas and Zaharaki, 2014). It has been observed that when agricultural waste is not managed properly, it can pollute both terrestrial and aquatic ecosystems.

10.3.1 Terrestrial ecosystem

Ecosystem services are significantly impacted by agricultural waste. Regular use of pesticides contaminates the air, water, soil, non-target organisms, and agricultural ecosystems. Fields treated with insecticides often result in the frequent death of birds. Certain pesticides cause direct bird deaths when birds consume the granules, believing them to be food grains. DDT and its byproducts cause thinning of eggshells, particularly in the population of birds in Europe and North America. In the 1950s and 1960s, the use of organochlorine (OC) pesticides in seed treatment resulted in a decrease in eggshell thickness, which led to the decline of sparrow hawks. The decrease in plants and invertebrate species that birds eat is assumed to be proof of the indirect effect of pesticides. Neonicotinoid treatment of a single maize kernel has the ability to kill songbirds. Imidacloprid when given to a little grain of wheat or canola can be hazardous to birds. Approximately one million bats have perished in the United States since 2006, with colony mortality reaching 90%. Exposure to organochlorine herbicides has also been connected, globally, to a drop in the number of bats. Animal poisoning primarily occurs when the food and water of animals are contaminated. Out of 2,205 bovine milk samples obtained from 12 different states in India, almost 82% of them had DDT residues. Punjab (51%) has the lowest amount of the sample with residues above the tolerance, followed by Himachal Pradesh (56%), Andhra Pradesh (57%), Gujrat (70%), and Maharashtra (74%) (Ansari, Moraiet, and Ahmad, 2014). Triazophos and dimethoate, two pyrethroid and organophosphate (OP) insecticides, are extremely toxic and dangerous to bees. The pollen and nectar from the plants sprayed with systemic insecticides such as imidacloprid and carbamates affect all bees. Imidacloprid appears to impact the bee's brain and metabolism, which lowers worker activity. When insecticides such as carbamate, pyrethroid, and organophosphate are used on vineyards, orchards, and other crops, the more vulnerable phytoseiid predators are reduced, which in turn leads to an increase in *Tetranychus* pests (Sanchez-Bayo, 2011).

10.3.2 Aquatic ecosystem

Water-based habitats are described as aquatic ecosystems where biotic and abiotic factors interact. Marine ecosystem and freshwater ecosystem are the two main categories of aquatic ecosystems. The marine ecosystem surrounds over 70% of Earth's surface and is the largest type of aquatic ecosystem, whereas below 1% of the surface of Earth is covered by a freshwater ecosystem (Bashir *et al.*, 2020). The current agricultural system is under pressure as a result of the recent rise in global population. The primary goal of the majority of countries is to boost food production in order to fulfill the demands of an expanding population. The agrochemicals including fertilizers, nematicides, fungicides, and herbicides are used for increasing crop yield. Pesticides are the most dangerous of all the hazardous compounds that seep into the aquatic

TABLE 10.1 **Impacts of agriculture waste on biodiversity degradation.**

A. Pesticides and Fertilizers		
Type	Impact on biodiversity	Reference
Organophosphate (Monocrotophos)	Killed 6,000 Swainson's hawks (Argentine pampas)	(Isenring, 2010)
Carbamate (Bendiocarb) Pyrethroids (Cypermethrin, delta-methrin, permethrin)	Poisoned bee colonies (UK)	(Isenring, 2010)
Metasulfuron and Chlorsulfuron	Reduced growth of soil bacteria pseudomonas	(Isenring, 2010)
Bromadiolone (Rodenticide)	Poisoning of foxes due to residues of bromadiolone in prey tissue (France)	(Isenring, 2010)
Chemical fertilizer (Nitrogen based)	Nitrate (basic fertilizer) causes water pollution resulting in "blue baby syndrome," acquired methemoglobinemia in newborns and ruminants and eutrophication Reduces the mycorrhizal activity in roots and suppresses rhizobial symbiotic nitrogen fixation	(Chandini, Kumar, and Prakash, 2019)
Chemical fertilizer (Nitrogen and phosphorus)	Causes eutrophication, which leads to the death of aquatic species and generation of unwanted species	(Chandini, Kumar, and Prakash, 2019)
Chemical fertilizer	Triple superphosphate fertilizers have traces of cadmium and arsenic elements that gather in plants and enter humans via food chain and cause health issues	(Chandini, Kumar, and Prakash, 2019)
B. Organic Wastes		
Sewage sludge	Content of phytotoxic heavy metal, soil salinity, and pathogenic microbes increased	(Hossain *et al.*, 2017)
Manure	Trigger leaching of phosphorus in soil	(Hossain *et al.*, 2017)
Municipal solid waste	Addition of heavy metals in soil Decrease in enzyme activity	(Hossain *et al.*, 2017)
C. Agro-Industrial Waste		
Pulp and paper industry (Organic and inorganic compounds)	Carcinogenicity, disruption of endocrine and mutagenicity like negative effects on aquatic ecosystem	(Singh *et al.*, 2021)
Poultry, aquaculture, and fertilizer industry	Runoff of nutrients can cause eutrophication (algal bloom) and disrupt aquatic ecosystem	(Singh *et al.*, 2021)
D. GMOs (Genetically Modified Organisms)		
GM potatoes	Cysteine proteinase inhibitor present in GM potatoes causes reduction in abundance of fungi and microbes	(Jha *et al.*, 2020)
GM rice	Chitinase present in GM rice causes reduction in intraradical fungi	(Jha *et al.*, 2020)

ecosystem since they pose substantial risk to all living organisms, including humans. Fish, amphibians, plants, microbes, invertebrates, and other categories of species make up the aquatic ecosystem. These organisms are susceptible to the direct or indirect effects of pesticides. Example of direct pesticide effect is the death of water fleas due to pesticide exposure, and an indirect effect of pesticide is the reduction of grazing pressure, which might result in a sharp increase in algal growth (Shefali *et al.*, 2021). The runoff from agriculture into watersheds following rainfall, especially extremely heavy rains, adds phosphate, nitrogen, and potassium in soil. Phosphorus and nitrogen are incorporated into streams as a result of fertilizer application to land. The presence of phosphate and nitrate can cause rivers to become eutrophic, endangering the life of downstream consumers, livestock, and wild creatures. The effects of eutrophication include fish death, cyanobacteria (blue-green algae) toxins, and issues with the water filtration process before use by humans.

Herbicides and fungicides are less harmful than insecticides. Compared to animals and birds, amphibians are more vulnerable. When endosulfan was sprayed on fields, tadpoles perished, and development defects were noticed. Application

of chlorpyrifos reduced the mass of tadpoles to 20-35%. In addition, 50% of the *Hyla regilla* population exposed to 190 ppb of organophosphate residues showed reduced cholinesterase. Endosulfan hindered the growth of African giant snail when it was applied repeatedly to cocoa fields.

10.4 Soil faunal diversity and soil degradation

Soil is considered the most precious resource on Earth. Soil is a multicomponent and multifunctional system that provides a variety of ecosystem goods including production of biomass for humans. Soil also provides numerous regulating services (e.g., decomposition of soil organic matter, maintenance of soil structure, cycling of nutrients) that guarantee the sustainability of ecosystems. The annelids (earthworms and enchytraeids), bacteria, collembolans (springtails), fungi, macroarthropods (such as spiders, Myriapoda, insects, and woodlice), mites (Acari), nematodes, and protozoans comprise the soil biota. It also encompasses plant roots and the substances they release, drawing a diverse array of organisms. Such microorganisms either consume these secretions directly or feed on the other microorganisms thriving near the roots; this zone is referred to as the rhizosphere (Briones, 2014). During the degradation of plant and animal matter, protists, bacteria, and fungi metabolize this degrading matter and produce minerals like phosphates and nitrates or organic waste products like CO_2 and other gases. These nutrients are required by the plants for their growth. By changing the microbial constitution of soil, pesticides can have an impact on these processes. Over a long period of time, applications of the systemic fungicide benomyl decreased the colonization of mycorrhizal roots by 80%. This, in turn, caused an indirect 33% decrease in the number of predatory nematodes that feed on fungi. At normal concentrations of captan, carbofuran, and mercury fungicides, suppression of the mycorrhizal symbiosis in crops has been documented, leading to stunted plant growth and reduction in output. The ability of the native soil microbial population to break down DDT is further diminished in soil contaminated with chronic arsenic and copper fungicides and also reduces the regeneration process of fungus. The majority of soil bacteria, such as nitrogen-fixing rhizobium, are suppressed by herbicides with glyphosate because it prevents the synthesis of aromatic amino acids (Sanchez-Bayo, 2011).

10.5 Impact of agricultural residue burning on biodiversity

After harvesting, the portion of the plant that remains in the field is known as crop residue. From 2003 to 2013, the output of agriculture leftovers is estimated to have increased by 33% globally. A total of 47% of crop residues are produced in the Asian continent, with America producing 29%, Europe producing 16%, Africa producing 6%, and Oceania producing 2% (Singh, 2018). The Ministry of New and Renewable Energy (2019) estimated that 500 million tons of crop leftovers are produced yearly. The majority of crop residues according to the same studies is used for fuel, animal feed, and other household and commercial uses, although 92 Mt of the 140 Mt surplus are burned each year. The states that produce the largest crop residues in India are Uttar Pradesh with 60 million tons of residues, Punjab with 51 million tons of residues, and Maharashtra with 46 million tons of residues. Cereals (millets, maize, rice, and wheat) comprise around 70% of all agricultural waste (Reddy and Goudra, 2023). Crop residues are burned in fields for three primary reasons: lack of labor, high expense of removing residue from the field, and an increase in the use of combines for crop harvesting. Burning crop residues depletes plant nutrients like N, P, K, and S (Singh, 2018). The National Policy for Management of Crop Residue (NPMCR) reports that burning 1 ton of straw results in complete degradation of organic carbon and 5.5 kg nitrogen, 2.3 kg phosphorus, and 1.2 kg sulfur lost (Bhuvaneshwari, Hettiarachchi, and Meegoda, 2019). There is variation in the composition and rate of breakdown of crop residue obtained from distinct cereal crops. Cellulose (38-50%), hemicellulose (23-32%), and lignin (15-25%) are the main constituents of lignocellulosic crop residue biomass, and they are bound together by a variety of multiple bonds. Crop residue's structural elements (cellulose, hemicellulose, lignin, and polyphenols) and nutritional composition, particularly C/N, are assumed to be the main indicators of the conditions under which it would decompose. Crop residue with a high hemicellulose concentration decomposed quickly, but crop residue with high ratio of C/N and high lignin content decomposed more quickly. There have been numerous adverse effects of burning crop residues on environmental health (Singh *et al.*, 2018). Studies conducted over long and short periods of time in Canada, Australia, and the United States have found that burning crop wastes and grasslands for an extended period of time degrades soil quality, which is directly linked to lower productivity (Mishra *et al.*, 2014). Frequent burning destroys beneficial microflora and fauna, lowers the soil's potential for retaining carbon as well as nitrogen, and further loses a significant amount of organic matter. The heat produced by burning the wastes increases the temperature of soil and reduces the number of bacteria and fungi (Bhuvaneshwari, Hettiarachchi, and Meegoda, 2019). Compared to unburned fields of straw, soil organic carbon (SOC) in burned straw fields decreases in both higher and lower depths. In addition, burning of straw results in lowering the available content of nitrogen (Mishra *et al.*, 2014). Burning of crop residues also

causes the release of greenhouse gases that accelerate global warming, raises smog and particulate matter (PM) concentrations that are harmful to human health, and causes deterioration of soil fertility, habitat degradation, and extinction of biodiversity in agricultural regions (Reddy and Goudra, 2023).

10.6 Impact of agriculture waste on greenhouse gas emission

Globally, the emission of GHGs from the agriculture sector, specifically carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), is rising due to human activities. Human activity is primarily to blame for altering Earth's climate because of absorption and reemitting energy from the Earth's lower atmosphere. The potential of CH_4 and N_2O for global warming is 21 and 310 times greater, respectively, despite their emissions being lower than that of CO_2 (Chataut *et al.*, 2023). The scientific community has paid exceptional attention to research focused on grain production and lowering emission of greenhouse gases from agricultural land as a result of growing concern of the international community about climate change, lower emission of greenhouse gases, and food safety. One of the main causes of greenhouse gas emissions is agriculture. Among them, animal manure has resulted in CH_4 emissions of 2.86×10^6 t and N_2O emissions of 2.66×10^5 t, which together account for 28.35% of the total N_2O from agricultural practices; additionally, 5.2% of the N_2O from animal manure comes via compost (Huang *et al.*, 2019). Soil retains a significant amount of organic carbon, and approximately 10% of CO_2 in the atmosphere travels via terrestrial soil annually. This illustrates the role that soil plays in the release of greenhouse gases (Chataut *et al.*, 2023). In Asia, improper irrigation techniques have resulted in increased salinization and emission of methane, while excessive nitrogen fertilizer use resulted in emission of damaging greenhouse gases. As a result, the agricultural sector is one of the main factors responsible for carbon, nitrous oxide, and methane emissions, as well as a major contributor to worldwide deforestation.

10.7 Policy implications and knowledge gaps

The Indian government has made several attempts through government-initiated programs to educate farmers on handling agricultural waste. Government representatives and environmentalists have also launched an assortment of forums and ideas to promote the use of alternative sustainable management methods and prevent the burning of agricultural leftovers (Bhuvaneshwari, Hettiarachchi, and Meegoda, 2019). The Essential Commodities Act of 1995 regulated fertilizer's sales, pricing, and quality in India. The Fertilizer Control India in 1957 was implemented by the government of India to execute management. This order was amended as the Fertilizer (Control) Order 1985 after undergoing many amendments. To promote the balanced use of fertilizers, India launched the nutrient-based subsidy program in 2010. However, this policy is unevenly implicated, particularly focusing on phosphorus and potassium fertilizers. Food loss and waste protocols provided guidelines, but comparing data from various sources is challenging, making it difficult to monitor the situation on a national scale. Price and market changes can have rebound effects, which entails eliminating waste in one area of the supply chain that can lead to an increase in waste in another. To effectively reduce food loss and waste (FLW), it must be essential to understand these relationships across the whole supply chain (Cattaneo *et al.*, 2021). The policies for crop residue management encourage methods like mulching and integrating leftovers into the soil to reduce crop residue burning practices and its detrimental effects on the environment. Several regulations govern crop residue burning, including Section 144 of the Civil Procedure Code, which prohibits burning of paddy. Even while government programs monitor and regulate crop burning, their efficacy is still uncertain because of insufficient stakeholder participation, education, and awareness campaigns (Bhuvaneshwari, Hettiarachchi, and Meegoda, 2019).

10.8 Sustainable approaches for agricultural waste management

Traditionally, agricultural waste was dumped untreated into the environment. It is necessary to treat waste as a resource to stop contamination of water, air, and land. For effective waste management, disposal techniques are utilized. For managing agricultural waste, the "3R" strategy focuses on minimizing waste through reuse, reduce, and recycle. Conservation farming practices should be implemented for crop residue management so that agricultural waste is converted into nutrient-rich compost, which increases soil moisture content, inhibits the growth of weeds, and helps to avoid soil erosion. By using vermicomposting methods, agricultural yield and nutrient absorption could be improved. Pyrolysis produces biochar, which helps the soil hold onto its minerals and water. Crop residue burning can be avoided by planting different crops and using different planting techniques. On-site residue management is made possible by mechanized techniques like happy seeders and zero-till seed drills, which enhance crop yields and produce better financial results (Reddy and Goudra, 2023). Agricultural waste improves anaerobic digestion by increasing microbial activity, which is essential for effectively turning

complicated substrates into biogas (Duque-Acevedo *et al.*, 2020). Farmers can use agricultural waste for energy production instead of burning. Utilizing the plant leftovers for other purposes can benefit the environment and provide opportunities to farmers for income generation. Agricultural waste can be used in diverse applications: banana peels are used as organic fertilizer, wheat bran is utilized for bio-alcohol production, and coconut shell is mixed with asphalt for construction of roads (Harshwardhan and Upadhyay, 2017). Agricultural waste can be used in bio-composites, particularly using nanocellulose as a sustainable enhancer. Nanocomposites are utilized in a wide range of applications, and nanocellulose integrated polymers are used in various products from medical to packing (Abdullah *et al.*, 2021). Moreover, linking incentives for recycling or source separation and spreading awareness and education among people could be the suggested approaches for proper management of agricultural waste. These strategies are not only helpful to manage waste but also create jobs, particularly in areas where labor is in high demand and governmental support for sustainability enforces eco-friendly methods for converting organic waste into compost and biogas as per the market demand.

10.9 Conclusion

Agricultural production is essential for feeding the world's population. It supplies raw ingredients for numerous sectors in addition to food. Globally, the ecosystem is seriously threatened by the careless dumping of agriculture waste, which includes pesticides, fertilizers, organic waste, agro-industrial waste, and waste from GMOs. There is an urgent need to address the enormous negative consequences of agricultural waste on habitat degradation and biodiversity loss. This waste results in contamination of air, soil, and water resources, which causes a decrease in species of plants and animals and deteriorates habitats. Multifaceted strategies are necessary to address these issues. Comprehensive policies that combine environmental preservation with sustainable agriculture should be implemented to address this issue. Policy-makers, environmental organizations, farmers, and researchers must work together to successfully implement and enforce laws intended to manage agriculture waste. Ultimately, agricultural waste management policies that prioritize biodiversity and habitat protection are essential for preserving ecosystem health, as well as for guaranteeing the long-term sustainability of agriculture and the accessibility of food for future generations.

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Chapter 11

The hidden dangers: Agricultural waste and its impact on human health

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Chapter Outline

11.1. Introduction 167
11.2. Agricultural wastes 168
11.4. Environmental impact of agro-wastes 171
11.5. Impact of agricultural waste exposure on human health 172
11.6. Conclusion 176
References 176

11.1 Introduction

Agriculture, cultivating food and related products through farming, is one of humanity's oldest and most crucial contributions to its survival and well-being (Golomazou *et al.*, 2024). From its modest origins as a practice of gathering food, agriculture has evolved into a vast, technology-driven industry. Even though modern agricultural techniques have been instrumental in boosting food production worldwide, they have also been a significant source of environmental pollution and waste generation. The cultivation and processing of agricultural products, including vegetables, fruits, poultry, meat, crops, and dairy, produce various agricultural waste. According to Zegardło *et al.* (2024), these wastes can be in liquid or solid forms depending on the specific agricultural activities. They may include food processing byproducts, animal manure, crop residues, and pesticides. With the increasing demand for agricultural products, the volume of agricultural waste is also expected to rise, and the agro-wastes, mainly those high in carbon content, are generated most from crops like rice, maize, wheat, cotton, and sugarcane (Wang *et al.*, 2024). Not all agricultural wastes are hazardous; the primary concern is those rich in toxic pollutants that can harm the environment and human health (Noor *et al.*, 2024). Therefore, it is essential to transform beneficial agricultural wastes into economically valuable products.

Although environmental pollution from agriculture is relatively limited, it does occur through emissions from agricultural machinery and the widespread practice of open burning of agricultural wastes, especially in developing countries. Agriculture is a significant contributor to the pollution of water and land resources and is the largest consumer of freshwater, accounting for an average of 70% of global surface water use (Kumar *et al.*, 2023). Recently, fertilizers and pesticides have increased in the forming sector, posing a risk to human health. Karimi *et al.* (2023) highlighted that in 2022, the global use of pesticides in agriculture hit a staggering 2.7 million tons, with Asia and the Americas contributing to nearly 80% of this total. Overuse of fertilizers can lead to nitrate contamination of underground water sources, posing a severe threat to human health.

Over the past few decades, the industrial-scale development of agriculture has led to numerous environmental and ecological challenges in both developed and developing countries. In response to these challenges, researchers are increasingly turning to management sciences. This chapter aims to provide an overview of the complexities associated with agricultural waste and its environmental impacts. The primary aim of this review is to carefully examine and synthesize the existing evidence on the effects of agricultural waste on human health. We explore the relationship between human health and particular types of waste generated in the agricultural sector. This book chapter also analyzes current research

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outcomes; the chapter seeks to provide a detailed assessment of the direct and indirect health implications, importance, severity, and range of health issues that can arise and could potentially result in the onset of specific diseases among the primary residents of agriculture areas. Conversely, the present chapter plans to provide a detailed understanding of the types, pathways, and health outcomes accompanying agricultural waste.

11.2 Agricultural wastes

The rapid growth of the global population has driven a threefold expansion in agricultural production over the past 60 years. Agricultural wastes can be broadly categorized into crop deposits, pesticides and fertilizers, livestock, agro-industrial byproducts, and food spoilage (Figure 11.1). Hence, agricultural products are essential to sustaining the world population; their production also has significant environmental and human health impacts. Agricultural waste originates from various sources, with a substantial portion coming from the use of pesticides. Moreover, agro-waste significantly impacts rural environments and, by extension, the global climate. Increased agricultural production has led to higher amounts of agro-industrial products, livestock waste, and crop residues. As developing countries intensify their farming systems, the rate of agro-waste generation is expected to rise. Of the total agricultural waste produced each year, about 80% is organic waste from farm activities, and mismanaged agro-waste negatively affects human health and the environment, making its management a significant concern (Albogami and Naguib, 2024). Many farmers and households generating this waste lack the knowledge to manage it properly, leading to issues, particularly air, soil, and water pollution from the dumping and burning of garbage, and yearly agro-waste augments by about 7.5%, exacerbating these ecological problems (Saharudin, Jeswani, and Azapagic, 2024).

11.2.1 Waste from crop deposits

Crop residues are a substantial component of agricultural waste, comprising the plant parts that remain in the field after the harvest of the main product. Conversely, managing crop residues presents opportunities and challenges, impacting soil health, environmental quality, and human health. Crop residues left on the field act as mulch, reducing soil erosion, retaining soil moisture, and contributing organic matter that improves soil fertility and microbial activity (Yang *et al.*, 2019). Moreover, deposits can be used as animal feed, raw material for bioenergy production, and inputs for composting, turning agricultural waste into valuable resources. Nevertheless, inappropriate management of crop deposits can lead to harmful conservation and health consequences. Open burning of crop residues releases a substantial amount of atmosphere toxins, including methane (CH_4), carbon monoxide (CO), and carbon dioxide (CO_2) (Adnane *et al.*, 2024). Crop wastes in the field can harbor pests and disorders, hypothetically affecting succeeding crops and increasing pesticide use (Jena and Singh, 2022).

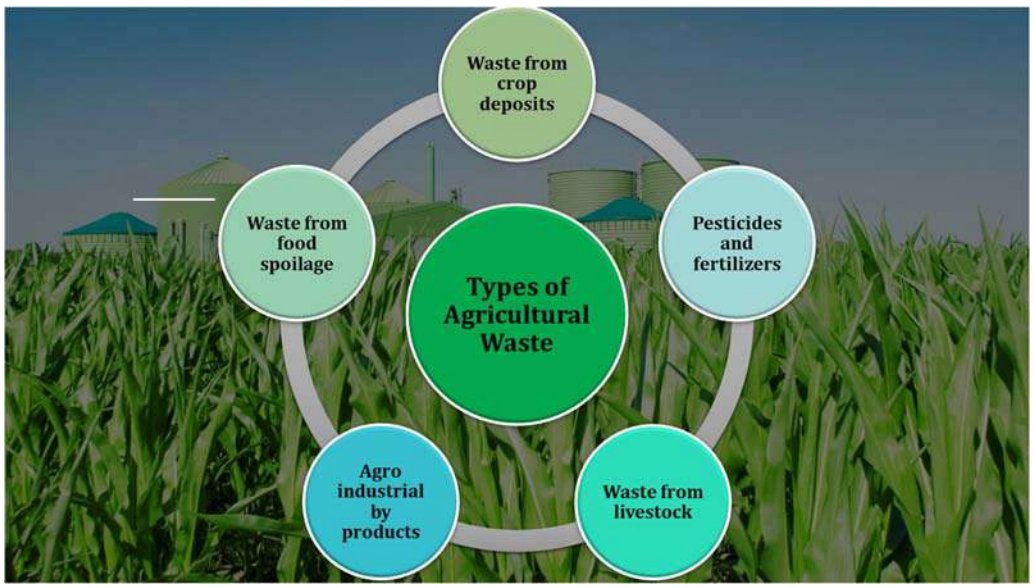


FIGURE 11.1 **Types of agricultural waste.**

11.2.2 Pesticides and fertilizers

Pesticides and fertilizers are integral to modern agricultural practices, playing a crucial role in enhancing crop yields and protecting plants from pests. According to Fayaz *et al.* (2024), chemical pesticides play a significant role in agriculture, with global usage increasing by approximately 20% from 2012 to 2022. Global pesticide usage in agriculture will reach 2.7 million tons in 2022. In recent years, Asia and the Americas were responsible for nearly 80% of global pesticide usage (Chen *et al.*, 2024). In 2015, the predicted global demand for fertilizer nitrogen was 184.02 million tons, with an expected increase to 186.67 million in 2016. By the end of 2020, this demand is projected to reach 201.66 million tons, growing at an average annual rate of 1.9% in subsequent years (Wen *et al.*, 2024). Pesticides' widespread and often random use has led to significant health and environmental concerns, requiring a careful assessment and the development of sustainable management practices. However, the extensive use of pesticides can lead to soil, water, and air contamination. Pesticides can persist in the atmosphere, accumulate in the food chain, and affect non-target organisms, birds, beneficial insects, aquatic life, and humans. Agricultural workers are directly impacted by pesticide exposure, with acute poisoning cases affecting a significant portion of the global population. Human exposure to pesticides can occur through various pathways, incorporating direct contact during application, inhalation of airborne deposits, and consumption of contaminated food and water (Figure 11.2) (Ruiz-González *et al.*, 2024). Chronic exposure to certain pesticides has been linked to a range of health issues, such as endocrine disruption, cancer, and reproductive problems. Chemical fertilizers, primarily nitrogen, phosphorus, and potassium compounds, enhance soil fertility and promote plant growth. Excess nitrogen and phosphorus from fertilizers can leach into groundwater, causing nutrient pollution and excessive algal blooms, which deplete oxygen levels in water, resulting in the death of aquatic organisms and the deprivation of water eminence. Moreover, due to environmental contamination, the abuse of fertilizers can disrupt soil health, and elevated levels of fertilizer use can alter soil pH and decrease soil organic matter.

11.2.3 Waste from livestock

Livestock production generates various types of waste, including manure, slaughterhouse discards, wastewater from cleaning cages, animal baths, sanitation processes, urinal discharges, and air pollutants. Consequently, air pollution results from the odors produced by the digestion of livestock waste, animal urine, and decomposing organic matter in manure. Untreated livestock waste contributes to greenhouse gas emissions, soil fertility degradation, and water pollution. Noteworthily, animal manure contains pathogens, such as bacteria, viruses, and parasites, which can contaminate the water and air environment and lead to risks of waterborne diseases to humans. Furthermore, in the early stages, farmers faced infections from parasites correlated with domesticated animals such as goats, cattle, and pigs. Effective livestock waste management is crucial to alleviating the current adverse effects and protecting human health and the ecological system. Environmental changes from land clearing and cultivation intensified human contact with arthropod vectors that carry diseases (Kenneth *et al.*, 2023). Waste from settled communities contributed to rivers' biological contamination, leading to human infections, including hookworm and *Escherichia coli*. Consequently, animal manure can also contain antibiotics,

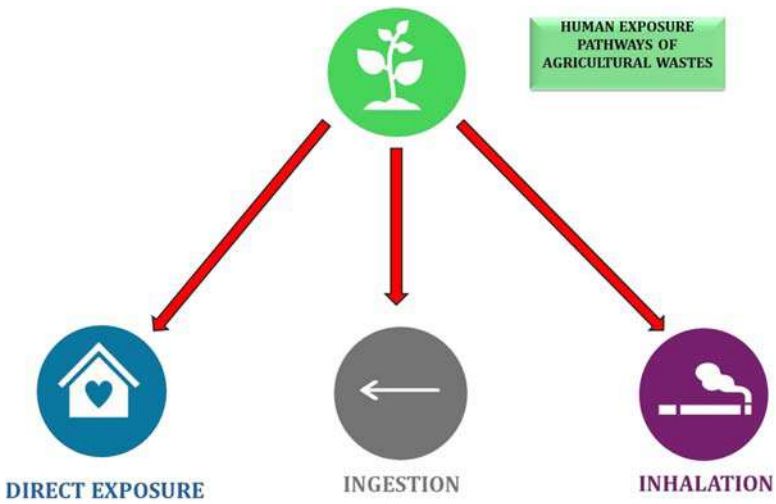


FIGURE 11.2 **Human exposure pathways of agricultural waste.**

heavy metals, and hormones used in livestock production. It can accumulate in the soil and enter the food chain, posing risks to human health.

11.2.4 Agro-industrial byproducts

Agro-industrial byproducts are the residual materials generated from the processing of agricultural commodities in industries such as food and beverage production; they comprise a diverse collection of materials such as husks, pulp, bagasse, molasses, shells, and wastewater (Rai and Kundu, 2024). Notably, the primary agro-industrial byproduct is bagasse, the fibrous residue left after juice extraction from sugarcane. Further, rice husks, another usual byproduct, are generated in large quantities during rice milling. Products such as seeds, peels, and pulp are abundant in the fruit and vegetable handling sector. Next is molasses, a thick, dark syrup left after sugar extraction from sugarcane. However, inappropriate agro-industrial ducts can lead to health risks. Moreover, wastewater from agro-industrial activities, particularly from dairies, breweries, and slaughterhouses, contains high levels of organic matter and nutrients. This wastewater can cause severe water pollution if untreated, harming aquatic ecological units (Hollas *et al.*, 2024). Hence, successful management of agro-industrial byproducts addresses waste disposal challenges and contributes to developing a disease-free world and environmental sustainability.

11.2.5 Waste from food spoilage

Appropriate drying progressions could significantly lower the spoilage of many agricultural products. Effective drying would enable farmers to combat food spoilage better and reduce agricultural solid waste, thereby augmenting food security and alleviating the negative impacts on human health. However, farmers depend on inaccurate solar drying systems and outdated humidity, examining ineffective methods. Insufficient humidity content observing grains before storing has led to aflatoxin infestation caused by the fungus *Aspergillus flavus*. Moreover, aflatoxin contamination in food and livestock feed results in substantial crop losses globally each year, and this contagion is both a cause and a consequence of food spoilage (Elamin, Sultana, and Sakuda, 2024). Furthermore, aflatoxins, particularly B1 and B2 produced by *A. flavus,* can cause hepatic cancer, injury to health in developing countries, and lead to significant economic losses.

11.3 Human exposure pathways

Understanding the exposure pathways of agricultural waste is significant in assessing and extenuating its impacts on human health, and these pathways describe how humans come into contact with different types of agricultural waste. Hence, the essential exposure pathways include direct contact, ingestion, and inhalation (Figure 11.2). Identifying the various exposure pathways of agricultural waste is vital to developing effective strategies to protect human health.

11.3.1 Direct exposure to agricultural waste

Direct exposure to agricultural waste presents significant health risks, particularly for those working in agriculture and near farming operations. This type of exposure occurs when a person physically comes into proximity with agricultural waste materials. Conversely, the impacts of direct contact can range from mild skin irritation to severe infections and enduring health concerns, depending on the nature of the waste and the duration of exposure. Notably, skin contact with fertilizer can lead to dermatological concerns, such as rashes and infections, due to the presence of pathogens, and it can enter the body through abrasions on the skin, potentially causing severe complaints. Farmers and agricultural workers are the most exposed to direct contact with agricultural waste, and they handle different waste materials as part of their daily activities, incorporating pesticides, spreading manure, and dealing with crop residues. Acute symptoms of pesticide exposure through direct contact include headaches, dizziness, nausea, and skin irritations, and long-term exposure can result in more dangerous health conditions such as neurological disorders and cancer (Ugwu and Enweremadu, 2023). Moreover, dust generated from handling dry residues can be inhaled, potentially causing respiratory problems, particularly in persons with respiratory problems such as asthma and allergies. Agro-industrial products containing fruit and vegetable pulp and husks can also pose health risks and contaminate with bacteria and other microorganisms that can cause allergic reactions. Furthermore, children living in agricultural zones are particularly vulnerable to the risks associated with direct contact with farm waste. They may play in fields where waste materials are present, enhancing their risk of exposure to harmful substances.

11.3.2 Ingestion of agro-wastes

Ingestion of agricultural waste materials is a dangerous exposure pathway that can significantly impact human health, and ingestion occurs when individuals consume food and water contaminated with hazardous substances from farm activities.

Hence, ingesting these toxins can hint at both acute and chronic health issues, depending on the nature and concentration of the toxins involved. Consumption of food containing pesticide deposits can stimulate a health problem. Furthermore, overflow from fields treated with nitrogen-based fertilizers and animal manure can contaminate surface and groundwater with nitrates. High levels of nitrates in drinking water can cause methemoglobinemia in children (Zhang *et al.*, 2023).

Additionally, manure excess can pioneer pathogens into water supplies, causing critical gastrointestinal (GI) illnesses and posing significant public health risks. Agricultural preparations, mainly using certain fertilizers and pesticides, can introduce heavy metals like cadmium, lead, and arsenic into the soil. However, crops grown in contaminated soil can absorb these metals, which then accumulate in edible plant parts. Noteworthily, chronic consumption of food contaminated with heavy metals can lead to severe health problems, including kidney damage, neurological disorders, cancer, and diabetes mellitus (Younas *et al.*, 2024). Secondary exposure can occur via animal products such as milk, meat, and eggs. Animals that consume contaminated feed and water can accumulate toxins in their tissues, which are passed to humans through the food chain.

11.3.3 Inhalation of agro-wastes

Inhalation of agro-wastes occurs when airborne particles and gases from agricultural works are breathed in, entering the respiratory system and potentially causing serious health issues (Ahmad *et al.*, 2023). Dust from crop residues is a common inhalation hazard in agricultural settings such as harvesting, plowing, and handling dried plant materials. Nevertheless, prolonged exposure to dust can lead to more rigorous conditions such as farmer lung, a type of hypersensitivity pneumonitis caused by repeated inhalation of organic dust. Gases emitted from animal manure and agro-industrial consequences pose inhalation hazards. Nevertheless, manure administration practices, particularly in large-scale livestock operations, can release ammonia (NH_3), CH_4, and hydrogen sulfide (H_2S) into the ecological system. NH_3 can cause respiratory irritation and lung damage, and H_2S can lead to life-threatening problems. CH_4, although not directly poisonous to human health in typical exposure situations, is a potent greenhouse gas contributing to climate change. Burning agricultural waste, such as crop deposits, is widespread in many regions, particularly India. Further, burning releases a substantial amount of smoke and harmful pollutants, including CO, volatile organic compounds, and polycyclic aromatic hydrocarbons. Inhalation of agrotoxins can cause various health issues, from immediate effects such as eye and respiratory tract irritation, coughing, and shortness of breath to lasting impacts such as chronic respiratory diseases and cardiovascular problems.

11.4 Environmental impact of agro-wastes

Improper handling of agro-wastes, which are laden with harmful toxins and pathogens, can spread diseases and the proliferation of dangerous chemicals, posing a risk of infection of people in healthcare environments (Surana *et al.*, 2022). Environmental contamination from agricultural waste is a pervasive issue affecting soil, water, and air quality, indicating extensive conservation and human health effects. Ecosystem interruption is a pronounced outcome of environmental contamination. Nevertheless, agricultural practices, including chemical fertilizers, pesticides, antibiotic products, livestock waste, and crop deposit waste, introduce various pollutants into the natural ecological system and pose chronic risks to human health (Pereira, Berenguer, and Câmara, 2023). Noteworthily, agricultural waste blanket dumping and burning lead to pollution and other environmental problems that demand global awareness. Hence, in farm venues, careless disposal of solid waste causes flooding and obstructs waterways. Pollutants from agricultural waste can destroy beneficial insects, disrupting ecological balance and reducing biodiversity. Aquatic ecosystems are exceptionally vulnerable to contamination, with nutrient overloads leading to algal blooms that can produce toxins harmful to fish, birds, and other animals. Conversely, the hysterical burning of agricultural solid waste influences climate-related emissions, and inappropriate organization of agricultural solid waste exacerbates climate change and hinders food production (Khanna, 2024). According to Chambers, Machray, and Fergie (2024), almost 7.5 billion people currently reside on the planet, with a significant number lacking sufficient food, and food insecurity has extensive adverse effects, including poor health and hindered educational and employment opportunities. Many toxic chemicals associated with agricultural waste have a high potential for environmental persistence and bioaccumulation in food chains. The World Health Organization (WHO) defines foodborne viruses as those caused by consuming contaminated food or water, and zoonoses, diseases originating from toxic invertebrate organisms emphasize the chronic health risks associated with the bioaccumulation of chemicals from pesticides (Utami *et al.*, 2024). Interestingly, several chemicals from agro-waste have slow metabolic rates in mammals, leading to their accumulation in tissues and eventual excretion in food products.

11.5 Impact of agricultural waste exposure on human health

The health effects of exposure to agricultural waste are distinct and impact people directly involved in agricultural occupations among broader communities through various conservation pathways. Noteworthily, the seriousness and nature of the health consequences depend on the type and concentration of the contaminants, the period of exposure, and the liability of the exposed populations. Consequently, exposure to agro-waste can have considerable penalties for human health, particularly in children, and they revealed that agricultural waste might cause spontaneous abortions, stillbirths, and premature births (Shittu *et al.*, 2023). Furthermore, their growth parameters, such as height, body mass index, weight, and chest circumference, may be poorly affected. Children exposed to these toxic chemicals from pesticides have lower cognitive and language scores. People exposed to agricultural waste may exhibit inhibited innate and adaptive immune responses. For instance, decreased antibody levels against vaccines (such as diphtheria and tetanus) have been reported. Moreover, cardiovascular risk factors include elevated systolic and diastolic blood pressure, increased heart rate, vascular inflammation, and adverse changes in blood morphology. Determined exposure to pesticides has been linked to a range of enduring health conditions involving endocrine disruption, which can affect reproductive health and maturity, and substantial evidence links chronic pesticide toxic chemicals exposure to neurological disorders (Lini *et al.*, 2024). Moreover, chronic exposure to heavy metals from agro-waste through contaminated soil and water can cause serious health issues such as cardiovascular diseases and renal and hepatic damage (Figure 11.3). Furthermore, mental health impacts are also emerging as significant consequences of exposure to agricultural waste, and studies have revealed that chronic exposure to certain pesticides may be linked to mental health (Cancino *et al.*, 2023).

11.5.1 Respiratory obstruction

Respiratory obstructions from introducing agricultural waste constitute a significant health concern and can lead to acute and chronic respiratory conditions. Agro-waste is a significant factor contributing to respiratory obstructions worldwide due to the inhalation of various pollutants. Globally, atmosphere agricultural waste toxic pollution is linked to a considerable burden of respiratory diseases and mortality, accounting for 29% of lung cancer cases, 17% of acute lower respiratory infections, and 43% of chronic obstructive pulmonary diseases (COPD) (Elonheimo *et al.*, 2022). Global Health Observatory data reports that among 3,541 patients admitted with respiratory diseases, 17.8% had COPD, 9.3% had lung cancer, and 7.4% suffered from acute lower respiratory tract infections. However, essential sources of respiratory hazards bring in particulate matter from burning crop residues, dust from soil and plant materials, aerosolized pesticides, and gases (Jestin-Guyon and Raherison-Semjen, 2024). Noteworthily, particulate matter from burning crop wastes is a substantial donor to respiratory problems, and when agricultural waste is burned, it releases enormous amounts of delicate



FIGURE 11.3 **Impact of agricultural waste exposure on human health.**

particulate matter (PM2.5 and PM10) into the atmosphere. Mechanistically, these particles can invade deep into the lungs and enter the bloodstream, causing instant respiratory annoyance and aggravating situations such as asthma and bronchitis (Green, Peterson, and Smith, 2023). Furthermore, longstanding coverage of delicate particulate matter is linked to more dangerous health outcomes, cardiovascular diseases, and lung cancer. In addition, inhaling smoke from burning crop wastes can lead to systemic inflammation, augmenting the risk of chronic respiratory and cardiovascular conditions. Dust from soil and plant materials is another ubiquitous respiratory hazard in agricultural circumstances; inhaling this dust can cause respiratory tract irritation, allergic reactions, and infections. Hulse *et al.* (2022) reported that constant exposure to agro-waste dust can hint at a condition known as farmer lung, a type of hypersensitivity pneumonitis considered by inflammation of the lung tissue and, if not appropriately managed, can cause permanent lung damage. Desperate inhalation of pesticides can induce instant symptoms such as wheezing, coughing, and shortness of breath; lasting exposure to some pesticides has been connected to chronic respiratory circumstances and neurotoxicity (Subbiah and Tiwari, 2021).

11.5.2 Skin irritation and ophthalmic discomfort

Exposure to agro-waste toxic chemicals can stimulate various skin abnormalities. It penetrates the skin through hair follicles and has been linked to inflammatory diseases such as acne, atopic dermatitis, and psoriasis. Tessema, Nagy, and Ádám (2022) highlighted a direct link between agro-waste toxins and allergic skin conditions, emphasizing agricultural waste's severe public health implications. Further, agro-waste toxins such as H_2S and NH_3 accompany skin rashes, eczema, itchiness, and malignant melanoma. Agricultural waste chemicals can cause a range of ocular discomforts, including burning, tearing, stinging, and photophobia, even in the absence of diagnosed eye diseases, often called discomfort eye syndrome. A recent study by Mohajer *et al.* (2022) found that 80% of farmers or agricultural workers suffered from ocular surface diseases, with 38% experiencing severe symptoms and 17% having abnormal tear secretion. Agro-waste toxins such as H_2S are strongly linked to ocular conditions like conjunctivitis and can alter the pH of tears, indicating irritation.

11.5.3 Cardiovascular dysfunction

On a global scale, agro-waste accounts for 2% of deaths from ischemic heart disease and 24% from strokes, occurrences of the highest cardiovascular burden from agro-waste toxins (Seferidi *et al.*, 2020). Agro-waste toxins and pesticides have been shown to augment low-density lipoprotein (LDL) levels and decline high-density lipoprotein (HDL), which can initiate dyslipidemia. However, raised LDL levels and declined HDL can lead to the accretion of cholesterol in the arterial walls, forming plaques that stimulate atherosclerosis. The condition can also reduce blood flow to the heart and brain, increasing the risk of heart attack. Nevertheless, endothelial dysfunction is a critical event in the pathogenesis of atherosclerosis and can lead to coronary artery disease. Agricultural toxic chemicals can reduce the bioavailability of nitric oxide (NO), and lowered NO levels lead to vasoconstriction, enhanced blood pressure, and a pro-thrombotic state, all of which are dangerous factors for cardiovascular diseases (Han *et al.*, 2024). Furthermore, chronic inflammation and oxidative stress influence the advancement and progression of cardiovascular diseases. In the cardiovascular system, reactive oxygen species (ROS) can lead to endothelial dysfunction, and the damaged endothelium becomes a site for inflammation, promoting the recruitment of immune cells and the release of pro-inflammatory cytokines (Pandher *et al.*, 2021). Agricultural waste toxins can disrupt calcium signaling pathways and interfere with voltage-gated calcium channels in cardiac cells, resulting in abnormal heart rhythms, reduced contractility, and reduced cardiac function (Truong, Feng, and Pessah, 2020). Mysteriously, agricultural waste toxins have direct toxic efficacy on cardiac tissues. For instance, they can inhibit acetylcholinesterase, which can accumulate acetylcholine and overstimulate the parasympathetic nervous system, leading to hypotension, bradycardia, and cardiac arrest in severe cases.

11.5.4 Reproductive disorders

It is well known that several agricultural waste chemicals are endocrine disruptors. They can mimic, block, and alter the natural hormones in the body, indicating disparities that affect reproductive health. Zhao *et al.* (2024) explored that atrazine has been shown to prompt aromatase activity, switching androgens to estrogens, thus disrupting the hormonal balance key for both male and female reproductive health. Agro-waste interaction can lead to endocrine disruption, significant oxidative stress, inflammation, and impaired oxygen supply to the placenta, increasing the risk of lower birth weight and preterm birth. Lin *et al.* (2023) have shown a strong correlation between high concentrations of agro-waste and instances of premature and underweight births. According to Kolan and Hall (2023), pregnant women admitted to hospitals found that 15.7% of deliveries were premature, and 23.7% of newborns had low birth weights due to exposure to agricultural toxins.

Agricultural waste toxins can induce oxidative stress by generating ROS, and free radicals can damage cells, including those in the reproductive organs. Sperm are particularly vulnerable to oxidative stress caused by various agricultural wastes, which can significantly impair male fertility. Oxidative stress injury to sperm cells can result in diminished sperm motility and viability, contributing to male infertility, and in women, oxidative stress can harm ovarian follicles, leading to impaired oocyte quality and decreased fertility. Agro-waste toxins have genotoxic properties; they can stimulate to injure genetic material and can cause mutations, chromosomal abnormalities, and disrupted cell cycles, which can distress reproductive health. Revealing heavy metals from agro-waste has been correlated to DNA damage in sperm cells, resulting in declined fertility and an augmented threat of miscarriages. Further, agricultural waste toxic chemicals can cause epigenetic changes, which are genetic in gene expression that do not involve variations to the primary DNA sequence and can affect reproductive health.

11.5.5 Gastrointestinal diseases

Agricultural waste has been found to have a significant long-term impact on the human digestive system. First, agricultural waste toxins can directly damage the epithelial cells lining the GI tract, resulting in ulcers, inflammation, and enhanced intestinal permeability. Rueda-Ruzafa *et al.* (2023) indicate that agro-waste induces environmental pollution and can reach the digestive tract through mucociliary clearance from the lungs and ingestion. Dioxin, a significant byproduct of burning agro-waste materials, is known to damage liver cells and cause over-secretion of enzymes, which can lead to GI and liver cancers and cases of GI distress, including appendicitis, which has been linked to ozone exposure (Wang *et al.*, 2024). The gut microbiota is essential for maintaining GI conditions, and agro-waste toxins like antibiotic residues can kill beneficial gut bacteria, causing pathogenic bacteria to replicate, leading to infections and inflammation. Nonetheless, agro-waste toxic chemicals can amend the assortment and profusion of gut microbiota, triggering imbalances that impact conditions like inflammatory bowel disease (IBD) and irritable bowel syndrome (IBS) (Chen *et al.*, 2024). Furthermore, certain agro-waste toxins have genotoxic properties, causing mutations and DNA damage in GI cells. Noteworthily, pesticides can induce genetic mutations, hypothetically causing cancerous growths, and heavy metals cause chromosomal aberrations and interfere with normal cell cycle regulation, enhancing the risk of colorectal cancer. Agro-waste toxins can inhibit enzymatic digestion, indicating absorption and triggering symptoms like diarrhea and swelling. Additionally, agricultural waste toxins also alter the immune system, leading to inadequate immune responses in the GI tract and changing the balance of immune cells in the gut, indicating conditions resulting in food allergies.

11.5.6 Cancer

The fundamental mechanism of agricultural waste toxins leading to cancer is through direct DNA damage and acquiring genotoxic properties. The agro-waste toxins can stimulate mutations by forming DNA adducts, causing DNA strand breaks and leading to malignant tumor formation (Liu *et al.*, 2022). Moreover, heavy metals from agro-waste inhibit DNA repair mechanisms, further encouraging the risk of genetic mutations and malignancy. The disruption of cellular signaling pathways can trigger oncogenes and inhibit tumor suppressor genes, indicating unconventional cell signaling and abandoned cell growth. Peillex and Pelletier (2020) reported that agricultural waste toxic chemicals often lead to the generation of free radicals, which cause significant oxidative damage to cellular components and can result in malignant development. Enduring and revealing agricultural waste toxins can lead to prolonged inflammatory responses, creating a microenvironment that facilitates tumor induction and development. Conversely, inflammatory mediators such as cytokines and chemokines promote cellular proliferation, survival, and angiogenesis, contributing to malignant tumor growth (Pugkhem *et al.*, 2024).

11.5.7 Diabetes mellitus

Many agricultural waste toxins act as endocrine disruptors, and endocrine disruptors interfere with the body's hormone systems, particularly insulin, which plays a crucial role in glucose homeostasis. Noteworthily, pesticides such as organophosphates, organochlorines, and carbamates alter hormone signals, disrupting the normal function of the antihyperglycemic hormone insulin, and it can lead to insulin resistance, resulting in augmented blood glucose levels and, ultimately, diabetes mellitus. Furthermore, chronic oxidative stress induced by agro-waste toxic chemicals can lead to β-cell dysfunction and apoptosis, reducing insulin secretion. Agricultural waste toxins can disrupt the balance of gut microbiota, leading to dysbiosis. They have also been linked to metabolic disorders such as insulin resistance and diabetes mellitus. Liu *et al.* (2021) described that disrupted gut microbiota could affect the fabrication of short-chain fatty acids, which play a significant role in maintaining insulin secretion and glucose homeostasis. Nevertheless, pesticides and heavy

metals from fertilizers can activate inflammatory pathways, leading to the release of pro-inflammatory cytokines like tumor necrosis factor-alpha (TNF-α), interleukin 6 (IL-6), and nuclear factor kappa B (NF-κB), and interfere with insulin signaling pathways, thus cumulative blood glucose levels (Tawar *et al.*, 2022). Agro-waste toxins exposure also alters T-cell-dependent immune responses, reducing insulin secretion and potentially damaging pancreatic β-cells. Moreover, pesticides and herbicides can accumulate in pancreatic tissue, leading to direct damage to β-cells and impair insulin secretion, influencing the development of diabetes mellitus. Miranda *et al.* (2023) identified mechanisms linking insulin resistance to pesticide exposure from agricultural methods, highlighting it as a substantial metabolic issue in gestational diabetes mellitus development.

11.5.7 Obesity

There is a link between agro-waste toxic chemicals and obesity, supported by theories suggesting biological and behavioral processes that connect agro-waste toxins to weight gain. Hence, agricultural waste toxins can influence body weight through several mechanisms. First, pesticide exposure disrupts glucose homeostasis, and agro-waste toxic chemicals may indirectly affect body weight by increasing the risk of chronic diseases (Miranda *et al.*, 2023). Furthermore, children near farming zones show higher rates of childhood obesity compared to those in urban areas. It underscores the multifaceted impact of agro-waste on health, including its contribution to the obesity epidemic.

11.5.8 Neurological disorders

Sustained-revealing agricultural waste has been linked with neurological impairments in both adults and children. Agro-waste toxic chemicals can initiate neuroinflammation, and it involves the activation of microglia and astrocytes, the resident immune cells of the central nervous system. Noteworthily, chronic neuroinflammation can result in neuronal damage and correlate with neurodegenerative diseases. Consequently, Shrestha *et al.* (2022) reported that pyrethroids can activate these glial cells, guiding the release of pro-inflammatory cytokines such as TNF-α, IL-6, and IL-1β. Interestingly, the brain is exposed explicitly to oxidative stress due to its high oxygen consumption and relatively low antioxidant defenses. It determined that oxidative stress can lead to neuronal cell death, contributing to neurodegenerative conditions. According to Interdonato *et al.* (2024), mitochondria are crucial for energy production in neurons, and agro-waste toxins can harm mitochondrial function, resulting in reduced ATP production and enhanced ROS generation.

Further, Sombatsawat, Siriwong, and Puangthongthub (2023) discovered that agro-waste toxins inhibit acetylcholin-esterase, resulting in the accumulation of acetylcholine, causing continuous stimulation of neurons, which can indicate neurotoxicity, seizures, and chronic cognitive deficits. However, Kulcsarova *et al.* (2023) reported that pesticides can disrupt tight junction proteins necessary for preserving blood-brain barrier integrity. They conceded that the blood-brain barrier allows more toxins to enter the brain, resulting in enhanced neuroinflammation and neurotoxicity, leading to damage to the frontal cortex and olfactory bulb, contributing to the onset of Parkinson's disease.

11.5.8.1 Depression

Depression is a mental health disorder with an estimated lifetime prevalence of 11%, occurring more frequently in women than men and showing increasing trends across the general population. Nevertheless, globally, depression is the 10th leading cause of disability-adjusted life-years (DALYs), which measure the burden of disease by accounting for both years of life lost and years lived with disability. In 2030, depression is expected to rank among the top three factors contributing to DALYs (Steffens, 2024). Noteworthily, agro-waste toxic chemicals trigger excessive inflammation. They can lead to the depletion of serotonin in the central nervous system, and this development encompasses the activation of the enzyme indoleamine 2,3-dioxygenase, necessary for tryptophan synthesis, which is crucial for serotonin synthesis. Research by Frengidou *et al.* (2024) has identified a link between depression and exposure to agro-waste, and they further detected these consequences are attributed to imbalances in neurotransmitters and hormones.

11.5.9 Infectious diseases

Agro-waste toxic chemicals can enhance antibiotic resistance. Nevertheless, the extensive use of antibiotics in agriculture, especially in livestock fabrication, leads to the delivery of antibiotic residues into the environment and can promote the selection and propagation of antibiotic-resistant microorganisms (Zhao *et al.*, 2023). Moreover, resistant microorganisms enter the human food chain; they can initiate infections that are challenging to treat with standard antibiotics, thwarting public health attempts to influence infectious diseases. The contamination of water sources by agro-waste toxins is another crucial pathway leading to infectious diseases. Surplus fertilizers, pesticides, and other chemicals from agricultural fields

often carry into rivers, lakes, and groundwater. It can establish constructive conditions for the growth of harmful microorganisms such as viruses, bacteria, and protozoa. However, contaminated drinking, cooking, and irrigation water can spread waterborne diseases. Likewise, the deprivation of soil conditions due to the deposit of agricultural waste toxins can affect the transmission of soil-borne diseases. Poor soil maintenance can diminish the biodiversity of soil microorganisms, many of which play a part in conquering pathogenic microbes, and it can lead to an upsurge in the occurrence of soil-borne pathogens, particularly pathogens causing tetanus and hookworm infections (Paul *et al.*, 2024). Furthermore, agricultural waste toxins can alter the ecological balance, affecting the populations of disease vectors such as ticks, mosquitoes, and rodents. Pesticides intended to control these vectors can sometimes have unintended consequences, such as killing off natural predators, and it can lead to a rise in vector populaces and a higher prevalence of vector-borne diseases.

11.6 Conclusion

Agriculture, fundamental for providing numerous resources to humanity, generates substantial agro-waste globally, including waste from chemical products used in farming, aquaculture, and households. The current book chapter has provided a complete assessment of the antithetical outcomes of agricultural waste on human health. Thus, the chapter highlights the complicated nature of the health impacts, which include respiratory concerns, skin disorders, gastrointestinal problems, neurological disorders, reproductive problems, cancer risks, diabetes mellitus, and infectious diseases. The key conclusions of this chapter are the identification of specific exposure pathways through which agricultural waste affects human health, and the present pathways include direct contact, inhalation, ingestion, and conservational pollution of air, water, and soil. Sustainable agricultural waste management has become problematic in developing nations like India, where growing populations exaggerate the challenge. Finally, this review delivers vigorous evidence of the influential health risks posed by agro-waste and calls for imperative action to address the stated issues.

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Part III

Waste management technologies for waste mitigation

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Chapter 12

Traditional and modern waste management technologies: Challenges and limitations

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Chapter Outline

12.1. Introduction 183
12.2. Overview of traditional agricultural waste management techniques 184
12.3. Evolution of modern agricultural waste management technologies 188
12.4. Critical challenges in traditional agricultural waste management 190
12.5. Limitations of modern agricultural waste management technologies 192
12.6. Integration of traditional and modern approaches 195
12.7. Technological innovations in agricultural waste management 197
12.8. Conclusion 198
AI Disclosure 198
References 199

12.1 Introduction

To meet the high demands of a growing population, there has been a substantial increase in livestock and crop production. This surge has led to the generation of agricultural wastes (AWs), as noted by (Tripathi *et al.*, 2019). Agricultural waste management is a critical facet of sustainable farming practices that aims to address the environmental, economic, and social challenges associated with the disposal of agricultural residues. As the global population continues to increase, the demand for food production escalates, leading to increased agricultural activities and, subsequently, a surge in waste generation. With the burgeoning global population, escalating food demands, and industrialization over the last century, the pursuit of high productivity has become a central objective in agricultural production; however, this focus has resulted in environmental degradation through waste generation, loss of biodiversity, and raised concerns about food security (Sheng, Cao, and Li, 2018). In light of these challenges, efficient agricultural waste management techniques and resource utilization have become imperative for fostering a resilient and sustainable agricultural sector.

This exploration into agricultural waste management delves into innovative and eco-friendly approaches to handle the byproducts of farming, emphasizing the importance of minimizing environmental impact and maximizing resource potential. This topic has garnered widespread attention from researchers, policy-makers, and practitioners alike, as it intersects with various disciplines such as environmental science, agronomy, engineering, and economics.

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Numerous studies highlight the pressing need for sustainable agricultural waste management, illustrating the potential benefits for both the environment and the agricultural community. Research by White *et al.* (2022) underscores the environmental consequences of improper waste disposal, emphasizing the role of responsible management in mitigating soil degradation and water pollution. Additionally, the economic viability of converting agricultural waste into valuable resources, shedding light on the potential for cost-effective and revenue-generating practices.

As we navigate the complexities of modern agriculture, understanding and implementing effective waste management techniques is paramount. This exploration aims to contribute to the growing body of knowledge surrounding agricultural waste management, offering insights that can inform sustainable practices and contribute to the overall resilience of our agricultural systems. By integrating cutting-edge research and practical solutions, this study seeks to pave the way for a more sustainable and resource-efficient future in agriculture.

12.2 Overview of traditional agricultural waste management techniques

12.2.1 Historical context of agricultural waste management

The historical context of agricultural waste management dates back to ancient civilizations where early farmers practiced rudimentary waste disposal methods such as composting organic matter. Throughout history, agricultural waste management evolved alongside advancements in farming practices and societal changes. During the Middle Ages, techniques such as crop rotation and manure spreading emerged to manage agricultural byproducts. The Industrial Revolution marked a significant shift, introducing mechanization and chemical inputs to agriculture, increasing productivity, and generating more waste (North and Thomas, 1977).

In the 20th century, concerns about pollution led to implementing regulations to address agricultural runoff and contamination. Modern agriculture faces challenges such as plastic waste from packaging and irrigation systems, as well as the impact of livestock waste on the environment. Plastics have emerged as a critical environmental issue in recent years, and their pollution significantly impacts soil, water, and plants (Gavigan *et al.*, 2020). Therefore, the historical context of agricultural waste management underscores the ongoing need for sustainable practices to balance agricultural productivity with environmental stewardship.

12.2.2 Water management in traditional agriculture

Water management in traditional agriculture plays a crucial role in crop production and waste management. In traditional agricultural practices, farmers often rely on methods passed down through generations, typically adapted to local environmental conditions. Some factors on how water management intersects with agricultural waste management in traditional farming are:

Irrigation techniques: Traditional agriculture often employs various irrigation techniques tailored to the local landscape and water availability. Techniques like flood, furrow, and drip irrigation are commonly used. Efficient irrigation methods help optimize water use, minimize runoff, and reduce soil erosion, contributing to better waste management by preventing nutrient-rich runoff from polluting water bodies (Taddesse, 2001).

Water harvesting: A solution to the water stress situation is using rainwater harvesting systems. Traditional farmers have developed ingenious methods for harvesting rainwater and surface runoff. Techniques such as building contour trenches, terracing, and constructing small dams and ponds help capture water during rainy seasons. This stored water not only serves as a crucial resource during dry periods but also aids in waste management by providing water for livestock, diluting agricultural waste for safer disposal, and supporting additional irrigation needs (Freni and Liuzzo, 2019; Amos *et al.*, 2020; Zhang *et al.*, 2019). The process presents economic benefits, especially for rural areas, and has presented some advantages in urban areas to supply the demand for non-potable purposes (Zdeb *et al.*, 2020).

Wastewater recycling natural filtration systems: This practice not only conserves water but also aids in waste management by utilizing organic nutrients in the wastewater, thus reducing the dependence on synthetic fertilizers. However, it is crucial to ensure proper wastewater treatment to avoid contamination of crops and soil.

In essence, water management in traditional agriculture is intricately linked with agricultural waste management. By employing sustainable water practices, traditional farmers can enhance crop productivity and mitigate environmental degradation caused by agricultural waste, contributing to the overall resilience and sustainability of their farming systems.

12.2.3 Traditional crop rotation systems

Traditional rotation systems are integral to sustainable agricultural practices, as they contribute to efficient agricultural waste management by promoting soil health, reducing chemical inputs, and enhancing overall ecosystem resilience. Bowles *et al.* (2020) supported the view that diversified crop rotation can effectively improve soil health and break the cycle of herbivores, weeds, and pathogens, increasing crop yields and bringing high economic benefits.

Traditional crop rotation systems are time-tested agricultural practices to maintain soil fertility and minimize pests and diseases. They typically involve alternating the types of crops grown in a particular field over consecutive seasons. Traditional crop rotation systems, as they relate to agricultural waste management, play a significant role in several ways:

Nutrient management: Different crops have varying nutrient requirements. Farmers can manage soil fertility more effectively by rotating crops, preventing the depletion of specific nutrients, and reducing the need for chemical fertilizers. This helps to minimize nutrient runoff and the accumulation of agricultural waste.
Pests and disease control: Continuous cultivation of the same crop in a field can lead to the buildup of pests and diseases specific to that crop. Crop rotation disrupts pest and disease cycles by introducing different plant species, reducing the need for chemical pesticides, and mitigating the accumulation of pesticide residues in the environment.
Soil health: Crop rotation enhances soil structure and microbial diversity, which improves soil health and reduces soil erosion. Healthy soils can absorb and retain water better, minimizing runoff and soil degradation, thereby reducing agricultural waste associated with soil loss.
Residue management: Different crops produce varying amounts of residues after harvest. Crop rotation allows for incorporating different crop residues into the soil, improving organic matter content and soil structure. This reduces the need for external inputs like synthetic mulches and minimizes agricultural waste associated with residue disposal.
Diversification and resilience: Traditional crop rotation systems promote agricultural diversity in crop species and genetic diversity within each species. Increased crop diversity over space and time is associated with improved soil health, pest control, decreased erosion, and increased nutrient cycling (Duru *et al.*, 2015). This diversification enhances ecosystem resilience to environmental stresses such as climate change, pests, and diseases, reducing the risk of crop failures and associated waste.

12.2.4 Use of cover crops for soil improvement

Cover crops are vital in soil improvement and agricultural waste management. These crops are planted primarily to cover and protect the soil rather than for harvest. They are a sustainable agricultural practice that prevents soil erosion, suppresses weeds, improves soil fertility, and enhances biodiversity. One of their significant benefits is their ability to manage agricultural waste effectively. Below are some of the significant importance of using cover crops for soil improvement.

Soil erosion control: Reducing water erosion is one of the main reasons for growing cover crops (Langdale *et al.*, 1991). Soils are generally more susceptible to erosion when not covered with the canopies of living plants or their plant residues. By covering the soil surface, cover crops reduce the impact of rainfall, wind, and other erosive forces, preventing soil erosion. This helps retain valuable topsoil and nutrients, otherwise lost to erosion. Cover crops with significant biomass are reported to reduce soil erosion, raindrop impact, and nutrient losses caused by high rainfall intensity (Kaye and Quemada, 2017).
Nutrient cycling: Certain cover crops, such as legumes like clover and vetch, can fix atmospheric nitrogen into the soil through symbiotic relationships with nitrogen-fixing bacteria. When these cover crops decompose, they release nutrients into the soil, enhancing soil fertility and reducing the need for synthetic fertilizers. Cover crop residue, particularly legume species with a low C/N ratio, can accumulate nitrogen concentrations. This accumulation enhances nitrogen availability for subsequent crops, decreasing the need for nitrogen fertilizer (Adetunji *et al.*, 2020).
Organic matter addition: Cover crops contribute organic matter to the soil as they decompose. This organic matter improves soil structure, water retention, and microbial activity, leading to healthier and more productive soils.
Weed suppression: Dense cover crop canopies shade out weed growth, reducing the need for herbicides. Certain cover crops inhibit weed growth while actively growing and continue suppressing weeds even after they have died (Blackshaw *et al.*, 2001). While growing, these cover crops fiercely compete with weeds for space, light, and nutrients. Once they do, they create a mulch layer on the soil surface, effectively stifling the emergence of subsequent weed growth (Gazoulis *et al.*, 2022). This natural weed suppression method helps manage agricultural waste by minimizing the spread of weed seeds and reducing the labor and resources required for weed control. Weed control operated by cover crops is a well-documented aspect of cover cropping (Osipitan *et al.*, 2019; Scavo and Mauromicale, 2021), both as a sole technique or within an integrated management strategy (Bhaskar *et al.*, 2021; Scavo and Mauromicale, 2020).

Disease and pest management: Some cover crop crops have allelopathic properties that can suppress weeds while breaking disease cycles and reducing bacterial and fungal disease populations (Everts, 2002). Cover crops, such as certain brassicas, release compounds that suppress soil-borne pathogens and pests. Certain cover crops serve as "trap crops," drawing pests away from the valuable crop and redirecting them toward what the pests perceive as a more suitable environment. Farmers can effectively manage agricultural waste associated with disease pressure and pest infestations by incorporating these crops into crop rotations.

Green manure: Cover crops can be used for soil fertility and quality management and are called green manuring. They can be grown specifically for incorporation into the soil before planting cash crops, acting as green manure. This practice adds organic matter, nutrients, and beneficial microorganisms to the soil, improving its overall health and productivity. Cover crops increase soil microbial activity, positively affecting nitrogen availability, nitrogen uptake in target crops, and crop yields (White *et al.*, 2022).

12.2.5 Community-based waste management initiatives

Community-based waste management initiatives are crucial in addressing agricultural waste management challenges. These initiatives involve the active participation of local communities in the collection, segregation, treatment, and recycling of agricultural waste. Waste management is essential for maintaining environmental sustainability and preventing pollution in agriculture. Community-based approaches empower residents to take ownership of waste management processes, fostering a sense of responsibility and cooperation within the community. Pigg (2009) delineates three dimensions of empowerment: individual action, organizational empowerment, and empowerment within social action contexts. This empowerment can be achieved by organizing and mobilizing people to act (Pigg, 2009). These initiatives often include various strategies such as composting, biogas production, and recycling. Composting agricultural waste can turn it into valuable organic fertilizer, reducing the need for chemical fertilizers and promoting soil health. Biogas production from agricultural waste, such as crop residues and animal manure, provides renewable energy and helps reduce waste and control odors.

Furthermore, community-based waste management initiatives promote awareness and education regarding the importance of proper waste disposal and its environmental impact. The significance of educating communities about waste management is undeniable within the broader context, as Nurhayati *et al.* (2023) emphasize. Education stands out as a pivotal tool in tackling the challenges associated with waste management, as acknowledged in research. Through workshops, training programs, and outreach activities, communities can effectively learn and implement sustainable waste management practices. By actively involving local communities, these initiatives address agricultural waste management and contribute to poverty reduction, job creation, and overall community development. They demonstrate the potential for decentralized, grassroots approaches to tackling environmental challenges while fostering a sense of environmental stewardship among residents. As indicated by numerous prior studies, the economic advantages of community waste management programs encompass additional income, economic incentives, and return on investment (Khan *et al.*, 2016; Kristanto *et al.*, 2015).

12.2.6 Traditional storage and preservation techniques

These traditional storage and preservation techniques are often sustainable, low-cost, and well-suited to local conditions. Traditional storage methods are knowledge that has evolved into the community and passed on from generation to generation (Natarajan and Santha, 2006). By using these methods, farmers can reduce waste, increase food security, and preserve the nutritional value of agricultural products. However, it is essential to balance traditional practices with modern innovations to meet the challenges of a changing agricultural landscape. Traditional storage and preservation techniques are integral to agricultural waste management, as they help farmers minimize waste and maximize the utilization of resources. These techniques have been developed over generations and are often rooted in local knowledge and practices. Farmers can reduce post-harvest losses by effectively storing and preserving agricultural products and ensuring a more sustainable food system. Post-harvest losses are a significant cause of concern worldwide, where below 5% of research funding has been allocated (Rajashekar, Bakthavatsalam, and Shivanandappa, 2012).

Traditional storage methods such as root cellars, silos, and granaries provide a means to store crops such as root vegetables and grains for extended periods, protecting them from spoilage and pests. Additionally, these storage structures help maintain the product's quality and nutritional value. Preservation techniques such as sun drying, smoking, fermentation, and salting enable farmers to prolong the shelf life of perishable foods such as fruits, vegetables, meats, and fish. Removing moisture or creating conditions unfavorable to microbial growth prevents spoilage and reduces the need for immediate consumption or refrigeration (Erkmen and Bozoglu, 2016).

Traditional storage and preservation techniques in agricultural waste management are crucial in reducing the amount of food lost or discarded due to spoilage or deterioration. By implementing these methods, farmers can minimize waste and contribute to increased food security, economic stability, and environmental sustainability within their communities. However, it is essential to complement traditional practices with modern technologies and best practices to address contemporary challenges such as climate change, globalization, and evolving consumer preferences.

12.2.7 Natural pest control in traditional agriculture

Natural pest control in traditional agriculture plays a crucial role in sustainable farming practices. Reducing the reliance on synthetic pesticides minimizes the environmental impact associated with pesticide runoff and contamination of soil and water resources. Additionally, promoting natural pest control methods aligns with the principles of integrated pest management (IPM), which prioritize environmentally friendly pest control approaches while ensuring farmers' economic viability. By reducing reliance on chemical pesticides, IPM promotes environmental health, preserves beneficial organisms, and minimizes the development of pesticide resistance (Karlsson Green, Stenberg, and Lankinen, 2020).

Moreover, the organic matter generated from agricultural waste can be used for composting, enhancing soil fertility and supporting the biodiversity of beneficial organisms involved in natural pest control. Therefore, integrating natural pest control methods with agricultural waste management strategies contributes to more sustainable and resilient farming systems.

12.2.8 Traditional techniques for post-harvest waste reduction

Traditional techniques for post-harvest waste reduction play a crucial role in agricultural waste management by minimizing losses and maximizing the utilization of harvested crops. These techniques have been employed for centuries and often involve simple yet effective methods to preserve, process, and store agricultural produce. Some standard traditional techniques include:

Drying: Drying is one of the oldest methods to reduce crop moisture content, preventing microbial growth and extending shelf life. It involves exposing harvested crops to sunlight or artificial heat sources until the desired moisture level is achieved.

Fermentation: Fermentation is a natural process that converts sugars and carbohydrates into alcohol or organic acids, creating an environment hostile to spoilage microorganisms. It is commonly used in the preservation of fruits, vegetables, and grains, as well as in the production of various fermented foods and beverages.

Pickling: Pickling involves submerging fruits or vegetables in a solution of vinegar, salt, and spices, creating an acidic environment that inhibits the growth of spoilage microorganisms. This method preserves the texture and flavor of the produce while extending its shelf life.

Smoking: Smoking is a preservation technique that involves exposing food to smoke from burning wood or other materials. The smoke contains antimicrobial compounds that help prevent spoilage and enhance flavor. Smoked meats, fish, and cheeses are famous examples of products preserved using this method.

Storage in root cellars: Root cellars are underground storage facilities designed to provide excellent, dark, humid conditions ideal for preserving fruits, vegetables, and root crops. Farmers can extend their shelf life by storing produce in root cellars and reduce post-harvest losses.

Sun-drying: Sun-drying involves spreading harvested crops on flat surfaces exposed to sunlight, allowing the heat to evaporate moisture and dehydrate the produce naturally. This method is commonly used for fruits, vegetables, herbs, and grains in regions with ample sunlight.

Crop rotation and polyculture: Traditional farming practices such as crop rotation and polyculture help maintain soil fertility, reduce pest and disease pressure, and minimize post-harvest losses. By diversifying crop species and alternating planting areas, farmers can mitigate the risk of crop failure and improve overall yield stability.

While modern technologies and innovations have introduced advanced methods for post-harvest waste reduction, traditional techniques play a significant role, particularly in rural and resource-constrained settings where access to sophisticated equipment and infrastructure may be limited. Integrating these traditional practices with modern approaches can offer holistic solutions for sustainable agricultural waste management.

12.2.9 Cultural and indigenous perspectives on waste management

Cultural and indigenous perspectives on waste management, particularly in agricultural waste management, offer unique insights and practices emphasizing harmony with nature and sustainable resource use. In many indigenous cultures, waste

is seen not merely as something to discard but as a valuable resource. Practices such as composting, recycling, and reusing are deeply ingrained in traditional knowledge systems. For instance, agricultural waste like crop residues and animal manure are often recycled back into the soil as organic fertilizers, enriching the land and promoting soil health.

Moreover, cultural beliefs often dictate a deep respect for the land and its resources, encouraging practices that minimize waste generation in the first place. Traditional farming methods, such as polyculture and agroforestry, prioritize biodiversity and resilience, reducing the need for synthetic inputs and minimizing waste outputs. Additionally, many indigenous communities view waste management as a communal responsibility rather than an individual one. Collective efforts such as community composting or shared waste disposal systems reinforce social cohesion and strengthen ties to the land.

By integrating these cultural and indigenous perspectives into modern agricultural waste management strategies, societies can not only reduce environmental impact but also promote resilience, sustainability, and respect for traditional knowledge systems. Embracing these perspectives fosters a holistic waste management approach that honors the earth and its inhabitants.

12.2.10 Challenges and adaptations in modern agriculture

In modern agriculture, managing agricultural waste presents various challenges and requires adaptive strategies to ensure sustainability. Challenges include the sheer quantity of waste generated, environmental impacts such as pollution and greenhouse gas emissions, regulatory compliance, optimizing resource utilization, and balancing economic viability.

To address these challenges, adaptations include the development of integrated waste management systems that combine techniques like composting and anaerobic digestion, leveraging technological innovations such as precision agriculture and data analytics, embracing circular economy principles to recycle and upcycle waste, providing education and outreach to farmers on sustainable practices, and implementing supportive policy frameworks at the governmental level. These adaptations maximize resource use, minimize environmental impact, promote sustainable practices, and foster stakeholder collaboration for a more sustainable agricultural sector.

12.3 Evolution of modern agricultural waste management technologies

12.3.1 Traditional agricultural waste management practices

Traditional agricultural waste management practices encompass a range of methods employed by farming communities over generations to handle agricultural byproducts effectively. These practices are deeply rooted in local knowledge, sustainability, and resource efficiency.

Composting is a central practice wherein organic residues like crop leftovers and animal manure are decomposed to produce nutrient-rich soil amendments. Mulching involves spreading crop residues on soil surfaces to suppress weeds, conserve moisture, and regulate soil temperature. Livestock integration allows animals to graze on crop residues, reducing waste while providing supplementary feed. Crop rotation is another critical strategy involving alternating crops to diversify residues and manage pests and diseases. Biomass utilization uses agricultural residues as fuel for cooking, heating, or energy generation, reducing reliance on nonrenewable sources. Traditional storage techniques often involve using crop residues to protect harvested crops from spoilage and pests.

Furthermore, biochar production, derived from organic waste through pyrolysis, enhances soil fertility and carbon sequestration. These traditional practices demonstrate a holistic approach to waste management, integrating organic materials into the agricultural ecosystem while maximizing resource efficiency and sustainability.

12.3.2 Challenges in conventional agricultural waste management

Introducing new waste management practices may face resistance or skepticism from stakeholders, including farmers, communities, and policy-makers. Lack of awareness, cultural norms, and perceived inconvenience can impede the acceptance and adoption of sustainable waste management practices.

Addressing these challenges requires a holistic approach integrating environmental, economic, and social considerations. This includes promoting awareness and education on sustainable waste management practices, incentivizing adoption through financial support and policy incentives, and fostering stakeholder collaboration to develop innovative solutions tailored to local contexts.

12.3.3 Emerging technologies in agricultural waste management

Emerging technologies in agricultural waste management are revolutionizing the sustainability of farming practices and addressing environmental concerns. These technologies focus on converting agricultural waste into valuable resources while minimizing negative impacts on ecosystems. Some of the key innovations are:

Biogas production: Anaerobic digestion processes convert organic waste into biogas, a renewable energy source mainly of methane and carbon dioxide. This technology generates clean energy and reduces greenhouse gas emissions from decomposing waste.

Biochar production: Biochar is a carbon-rich charcoal-like substance produced by heating biomass in a low-oxygen environment. It enhances soil fertility, sequesters carbon, and mitigates greenhouse gas emissions. Advanced pyrolysis techniques optimize biochar production from agricultural residues.

Precision farming: Using sensors, drones, and satellite imagery, precision farming optimizes resource utilization and minimizes waste in agriculture. By precisely targeting inputs like water, fertilizers, and pesticides, farmers can reduce excess usage and minimize environmental contamination.

Waste-to-energy technologies: Using agricultural waste for energy production has been adopted to different extents across the globe (Westerman and Bicudo, 2005). Beyond just generating income from the energy output, waste-to-energy initiatives provide an alternative and environmentally friendly method of waste management (Mackie, Stroot, and Varel, 1998). Various thermal and biochemical processes, such as gasification and pyrolysis, convert agricultural waste into heat, electricity, or biofuels. These technologies provide alternative energy sources while diverting waste from landfills.

Nutrient recovery: Technologies for recovering nutrients from agricultural waste, such as phosphorus and nitrogen, help close nutrient loops in farming systems. Processes like struvite precipitation and nutrient extraction from organic residues contribute to sustainable nutrient management.

Fungal bioremediation: Fungi-based bioremediation techniques utilize the natural abilities of certain fungi species to break down organic pollutants in agricultural waste. This approach offers an eco-friendly method for managing waste and reducing soil contamination.

Waste valorization: Innovative techniques aim to extract high-value compounds from agricultural waste, such as antioxidants, bioactive compounds, and fibers. These valorization processes create additional revenue streams for farmers while reducing waste.

Blockchain in waste management: Blockchain technology ensures transparent and traceable agricultural waste management by recording transactions and data across the supply chain. It enhances accountability, reduces fraud, and facilitates efficient waste management practices.

These emerging technologies hold great promise for sustainable agricultural waste management, promoting resource efficiency, environmental conservation, and economic viability in the agricultural sector. However, widespread adoption and integration into existing farming systems require further research, investment, and stakeholder collaboration.

12.3.4 Integration of information technology in agricultural waste management

Integrating information technology (IT) in agricultural waste management is revolutionizing how farmers and waste management professionals handle organic byproducts. IT tools such as sensors, drones, and IoT devices provide real-time data on waste production, composting processes, and biomass utilization. This data enables farmers to make informed decisions, optimize resource allocation, and remotely monitor waste facilities, reducing operational costs.

Moreover, IT solutions facilitate traceability and compliance with regulations governing waste management. Blockchain technology, for instance, enables farmers to track the journey of agricultural waste from production to disposal, ensuring compliance with environmental standards (Esposito, Ficco, and Gupta, 2021). Additionally, IT platforms foster knowledge sharing and collaboration among stakeholders, enabling the exchange of best practices and research findings.

Integrating IT in agricultural waste management enhances efficiency, reduces environmental impact, and promotes collaboration across the agricultural sector, leading to a more sustainable and resilient agricultural system.

12.3.5 Environmental and economic impacts of modern agricultural waste management

Modern agricultural waste management practices have significant environmental and economic impacts. On the environmental front, proper waste management can mitigate pollution, conserve resources, and protect ecosystems. However, inadequate management can lead to soil degradation, water contamination, greenhouse gas emissions, and biodiversity loss.

Effective waste management techniques such as composting, anaerobic digestion, and recycling can reduce the environmental burden by converting agricultural residues into valuable resources like biofuels, organic fertilizers, and animal feed (Koul, Yakoob, and Shah, 2022). This helps in minimizing waste accumulation, mitigating greenhouse gas emissions, and improving soil health through organic matter enrichment.

Furthermore, waste management practices can yield economic benefits by creating new revenue streams, reducing input costs, and enhancing farm profitability. For instance, selling agricultural residues for bioenergy production or utilizing them for on-farm energy generation can provide additional income. Sustainable waste management practices can also reduce the need for chemical fertilizers and pesticides, thus cutting production expenses and improving long-term soil fertility.

However, inadequate waste management practices can lead to economic losses due to environmental degradation, regulatory fines, and health-related costs. Pollution incidents resulting from improper disposal of agricultural waste can harm human health, contaminate water sources, and damage neighboring ecosystems, leading to costly cleanup efforts and legal liabilities (Wang *et al.*, 2015).

12.3.6 Biological approaches to waste management

Biological approaches to agricultural waste management use living organisms to degrade, transform, or utilize waste materials from agricultural activities. These approaches offer environmentally friendly and sustainable solutions to the challenges posed by agricultural waste. This approach includes:

Composting: Composting is a natural process where microorganisms break down organic materials such as crop residues, manure, and plant debris into nutrient-rich compost. This compost can improve soil fertility and structure, reducing the need for chemical fertilizers (Ayilara, 2020).

Anaerobic digestion: Anaerobic digestion involves the breakdown of organic materials without oxygen by microorganisms, producing biogas (a mixture of methane and carbon dioxide) and digestate (Meegoda, 2018). Biogas can be used as a renewable energy source, while digestate can be used as a nutrient-rich fertilizer.

Bioconversion: Bioconversion processes use microorganisms such as fungi, bacteria, and algae to convert agricultural waste into valuable products. Microbial biotechnology and nanotechnology are crucial in transforming agricultural waste into valuable products. In the pharmaceutical sector, they facilitate the production of enzymes and bioactive compounds. In agriculture, they contribute to the creation of vermicompost, organic fertilizers, and biofuels. Additionally, these technologies are instrumental in developing nutraceuticals and food products (Bala *et al.*, 2022). For example, certain fungi can be employed to convert crop residues into enzymes or biofuels, while bacteria can be used to produce bioplastics from agricultural byproducts.

Phytoremediation: Phytoremediation involves using plants to remove, degrade, or stabilize contaminants in soil and water (Ashraf *et al.*, 2019). Certain plant species can absorb and accumulate heavy metals, pesticides, and other pollutants from agricultural waste streams, detoxifying the environment.

Insect-based waste management: Insect larvae such as black soldier flies and mealworms can be utilized to process organic waste materials, including crop residues and manure, into protein-rich insect biomass and nutrient-rich compost (Surendra *et al.*, 2020). This approach reduces waste volume and produces valuable byproducts for animal feed and organic fertilizers.

By harnessing the power of biological processes, agricultural waste management can be transformed into a resource-efficient and sustainable practice, benefiting both the environment and agricultural productivity.

12.4 Critical challenges in traditional agricultural waste management

12.4.1 Resource efficiency

Resource efficiency in agricultural waste management refers to effectively utilizing resources within the agricultural sector to minimize waste generation, optimize resource use, and promote sustainability (Damian, Devarajan, and Jayabal, 2024). Agricultural waste, including crop residues, animal manure, and processing byproducts, presents challenges and opportunities. Agricultural waste can be transformed into valuable resources by adopting resource-efficient practices, such as composting, anaerobic digestion, and bioenergy production.

Composting involves decomposing organic waste to produce nutrient-rich compost, which can be used as a soil amendment to enhance fertility and improve crop yields. Converting agricultural byproducts like crop residues and animal manure into organic fertilizers through composting is a waste management technique that enables the utilization of organic

waste as fertilizer, even in densely populated regions (Sabiiti, 2011). Anaerobic digestion utilizes microorganisms to break down organic matter without oxygen, producing biogas for energy generation and nutrient-rich digestate for soil enrichment. Furthermore, agricultural waste can be utilized for bioenergy production through biomass combustion and biofuel production. Farmers can reduce reliance on fossil fuels by harnessing agricultural waste's energy potential and contributing to climate change mitigation efforts.

In addition to energy and nutrient recovery, resource-efficient agricultural waste management practices help mitigate environmental pollution and reduce greenhouse gas emissions. By closing the loop on waste streams and promoting circular economy principles, resource efficiency in agricultural waste management contributes to the sustainable development of the agricultural sector.

12.4.2 Environmental impact

Addressing the environmental impacts of agricultural waste management requires implementing sustainable practices such as composting, anaerobic digestion, and recycling (Maji *et al.*, 2020). Additionally, promoting awareness among farmers about the importance of responsible waste management and providing incentives for adopting environmentally friendly practices can help mitigate these impacts and promote a more sustainable agricultural sector.

Agricultural waste management significantly impacts the environment, both positively and negatively. On the positive side, proper management practices like composting can reduce greenhouse gas emissions by preventing organic materials from decomposing anaerobically, which produces methane. Additionally, recycling agricultural waste into biofuels or organic fertilizers can mitigate the reliance on fossil fuels and synthetic fertilizers, respectively, thus reducing carbon emissions and preserving soil health.

However, inadequate waste management can lead to numerous environmental problems. For instance, improper disposal of agricultural chemicals, such as pesticides and fertilizers, can contaminate soil and water sources, harming terrestrial and aquatic ecosystems. Moreover, accumulating organic waste in landfills can generate methane, a potent greenhouse gas, exacerbating climate change. Runoff from farms carrying sediment, nutrients, and pathogens can also degrade water quality, leading to eutrophication, harmful algal blooms, and threats to aquatic biodiversity.

Sustainable agricultural practices and proper waste management techniques, such as composting, recycling, and adopting precision farming methods, are essential to mitigate these negative impacts. Moreover, implementing regulations, promoting education and awareness among farmers, and investing in research for innovative waste management solutions can help minimize the environmental footprint of agricultural activities.

12.4.3 Climate change resilience

Climate change resilience in agricultural waste management is crucial for sustainable farming practices and environmental protection. Agricultural waste, including crop residues, animal manure, and food processing byproducts, presents challenges and opportunities in the face of climate change. Efficient agricultural waste management is essential to mitigate greenhouse gas emissions, such as methane and nitrous oxide, which contribute to global warming. Implementing practices like composting, anaerobic digestion, and biochar production can reduce emissions and produce valuable resources such as organic fertilizers and renewable energy.

Furthermore, proper waste management strategies can enhance soil health and fertility, contributing to the resilience of agricultural systems against climate-induced stresses such as droughts and floods. Practices like mulching with crop residues can improve soil moisture retention and reduce erosion, helping crops withstand extreme weather events.

Investing in innovative technologies and knowledge-sharing platforms can empower farmers to adopt climate-smart waste management practices. Policy support and financial incentives are essential to promote sustainable waste management across agricultural supply chains.

In essence, prioritizing climate change resilience in agricultural waste management is not only environmentally responsible but also economically beneficial, fostering a more sustainable and resilient agricultural sector in the face of a changing climate.

12.4.4 Cross-sector collaboration

Cross-sector collaboration in agricultural waste management involves various stakeholders from different sectors working together to address the challenges associated with agricultural waste. This collaboration brings together farmers, government agencies, nongovernmental organizations (NGOs), research institutions, and private industries to find sustainable solutions for managing agricultural waste.

Cross-sector collaboration in agricultural waste management is essential for addressing the complex challenges associated with agricultural waste while promoting sustainable development in rural areas. Collaborative efforts can lead to more holistic and practical solutions for managing agricultural waste by leveraging diverse stakeholders' expertise, resources, and perspectives.

12.4.5 Environmental impact and sustainability

Agricultural waste management plays a critical role in both environmental impact and sustainability. Agricultural activities generate significant waste, including crop residues, animal manure, and byproducts from processing. Improper management of these wastes can lead to various environmental issues such as soil degradation, water pollution, greenhouse gas emissions, and habitat destruction.

Effective agricultural waste management is essential for minimizing these negative impacts and promoting sustainability. One approach is through waste reduction and resource optimization. Composting, anaerobic digestion, and bioenergy production can convert agricultural waste into valuable resources like organic fertilizers and renewable energy, reducing the need for synthetic inputs and fossil fuels.

Furthermore, proper waste management practices can help mitigate climate change by reducing methane emissions from decomposing organic matter and sequestering carbon in soil through practices like conservation tillage and agroforestry.

Promoting sustainable agricultural waste management requires collaboration among farmers, policy-makers, researchers, and the private sector. By implementing integrated waste management strategies that prioritize environmental protection, resource conservation, and economic viability, we can build a more resilient and sustainable agricultural system for the future.

12.5 Limitations of modern agricultural waste management technologies

12.5.1 Cost constraints

While essential for sustainable farming, modern agricultural waste management technologies face significant cost constraints that limit their adoption and effectiveness. These constraints can be broadly categorized based on the following subheadings:

High initial investment: Implementing advanced waste management systems such as anaerobic digesters, biochar production, and sophisticated composting facilities requires substantial capital outlay. For example, installing an anaerobic digester can cost hundreds of thousands to millions of dollars, making it a prohibitive expense for many small to medium-sized farms (Sakar, Yetilmezsoy, and Kocak, 2009).

Operational costs: Beyond the initial investment, the ongoing operational costs of maintaining and running these technologies can be significant. These include energy consumption, labor, maintenance, and regulatory compliance costs. High operational costs can reduce the overall cost-effectiveness of these systems, mainly if the market prices for the end products (e.g., biogas and compost) are low (Kothari, Tyagi, and Pathak, 2010).

Economic scalability: The economic benefits of advanced waste management technologies often depend on achieving a particular scale of operation. Small-scale farms may find it challenging to reach the economies of scale necessary to make these technologies financially viable ("Agricultural Pollution: Environmental and Economic Costs," 2021). This scalability issue can create a barrier to widespread adoption among smaller agricultural operations.

Market and policy factors: Market prices for agricultural waste byproducts and government policies also influence the financial viability of waste management technologies. Inconsistent policies and a lack of subsidies or financial incentives can deter investment in such technologies. The fluctuating prices of byproducts like biogas or biochar can also impact the return on investment.

While modern agricultural waste management technologies offer significant environmental benefits, high costs often hinder their adoption. These constraints highlight the need for supportive policies, financial incentives, and technological advancements to reduce costs and make these technologies more accessible and economically feasible for a broader range of agricultural producers. By addressing these cost constraints through policy interventions, financial incentives, and technological advancements, the adoption of modern agricultural waste management technologies can be more feasible and widespread.

12.5.2 Technology complexity

Technology complexity is a significant limitation in adopting and implementing modern agricultural waste management technologies. This complexity has associated and essential aspects:

Specialized knowledge and skills: Modern agricultural waste management systems, such as anaerobic digesters, gasification, and advanced composting, often require specialized knowledge and technical skills for operation and maintenance (Insam and de Bertoldi, 2007). Farmers may lack the necessary training or expertise, creating a barrier to practical use.
Operational challenges: Complex technologies can pose operational challenges, including the need for precise control of parameters such as temperature, pH, and moisture levels. For example, anaerobic digestion processes require careful monitoring and adjustment to maintain optimal conditions for microbial activity (Insam and de Bertoldi, 2007).
Integration with existing systems: Integrating advanced waste management technologies with existing farm operations can be complicated. This integration often involves retrofitting current systems, which can be technically challenging and costly, especially for smaller farms without technical support.
Maintenance and troubleshooting: High-tech waste management systems may require frequent maintenance and troubleshooting, which can be difficult without specialized technical support. Breakdowns or inefficiencies can lead to disruptions in farm operations and additional costs.
Data management and analysis: Some modern technologies involve sophisticated data collection and analysis to optimize performance. Farmers may need to manage and interpret large volumes of data, requiring familiarity with digital tools and software they may not possess.
Regulatory compliance: Compliance with environmental regulations related to waste management technologies can be complex. Understanding and meeting these regulatory requirements necessitates familiarity with legal and technical standards, which can be daunting for farmers.

12.5.3 Accessibility and affordability

Modern agricultural waste management technologies have significantly advanced in recent years, and yet their accessibility and affordability present notable limitations. Factors to be considered under Accessibility include:

Infrastructure requirements: Advanced waste management technologies often necessitate substantial infrastructure, which can be lacking in rural or underdeveloped regions. For instance, technologies like anaerobic digestion require sophisticated equipment and reliable power supplies, which are not universally available.
Technical expertise: Implementing and maintaining these technologies demands specialized knowledge and training. Farmers in many parts of the world may not have access to the necessary education or support to utilize these systems effectively.

Factors to be considered under Affordability include:

High initial costs: The capital investment required for modern waste management systems can be prohibitively high. Equipment for composting, biochar production, or biogas generation can be expensive, limiting their adoption among small-scale or low-income farmers.
Operational and maintenance costs: Beyond initial investments, the ongoing costs associated with operating and maintaining these technologies can be significant. This includes energy costs, spare parts, and labor for regular maintenance, which can strain the budgets of agricultural operations.

12.5.4 Integration with traditional practices

Integrating modern agricultural waste management technologies with traditional practices faces several limitations, impacting their effectiveness and adoption. The integration of modern agricultural waste management technologies with traditional practices presents several challenges, including cultural resistance, compatibility issues, knowledge gaps, and economic constraints. Addressing these limitations requires tailored approaches that respect and incorporate traditional knowledge, provide adequate training and support, and offer financial assistance to ensure broader adoption and practical integration.

12.5.5 Maintenance challenges

Modern agricultural waste management technologies face several maintenance challenges that hinder their effectiveness and efficiency (Xiao *et al.*, 2020; Lim *et al.*, 2019). These challenges can be broadly categorized as follows:

The complexity of systems: Modern waste management technologies often involve complex machinery and processes requiring specialized knowledge and skills to operate and maintain. The sophistication of equipment such as anaerobic digesters, biochar production units, and advanced composting systems means regular maintenance can be time-consuming and costly. This complexity can lead to downtime and reduced efficiency if not appropriately managed.
Cost of maintenance: The financial burden of maintaining advanced waste management technologies is significant. Substantial ongoing maintenance expenses often accompany high initial investment costs. These costs include the need for specialized technicians, expensive spare parts, and regular updates or upgrades to the systems. For many agricultural operations, particularly smaller ones, these costs can be prohibitive, limiting the adoption and sustained use of these technologies.
Technological obsolescence: Rapid technological advancements mean agricultural waste management systems can quickly become outdated. Keeping up with the latest technology requires continual investment, which can strain resources. Moreover, parts and expertise for older systems become more challenging to find over time, further complicating maintenance efforts.
Environmental and operational conditions: Agricultural environments can be harsh and variable, affecting the longevity and functionality of waste management technologies. Factors such as exposure to the elements, dust, and varying temperatures can lead to wear and tear, corrosion, and other forms of deterioration. This necessitates frequent maintenance to ensure the systems remain operational under these challenging conditions.
Regulatory and compliance issues: Compliance with environmental regulations often requires that waste management technologies meet specific standards, which can necessitate regular inspections and maintenance to ensure ongoing compliance. This adds another layer of complexity and cost to the maintenance process, as noncompliance can lead to fines and other penalties.

12.5.6 Environmental impact

Modern agricultural waste management technologies, while designed to mitigate the environmental impact of agricultural waste, come with their own set of environmental limitations. These limitations can lead to various adverse effects:

Greenhouse gas emissions: Technologies such as anaerobic digesters manage organic waste and produce biogas. However, if not properly managed, these systems can leak methane, a potent greenhouse gas. Inefficiencies in gas capture and storage can thus contribute to greenhouse gas emissions, counteracting the environmental benefits they should provide.
Resource consumption: Advanced waste management technologies often require significant amounts of water, energy, and other resources for operation. For instance, aerobic composting systems and biochar production facilities consume water and energy. This resource consumption can lead to a substantial environmental footprint, particularly in regions with scarce resources.
Waste residues: The processes involved in modern waste management technologies can generate secondary waste products that must be managed. For example, biochar production can result in residues that contain contaminants or require additional treatment (Oni, Oziegbe, and Olawole, 2019). Similarly, the effluent from anaerobic digesters needs careful handling to prevent soil and water contamination.
Soil and water contamination: Mismanagement or failure of waste treatment systems can lead to soil and water body contamination. Leachate from improperly managed composting operations or runoff from biochar facilities can introduce nutrients and pollutants into the environment, causing eutrophication of water bodies and degradation of soil health.
Biodiversity impacts: Deploying large-scale waste management facilities can disrupt local ecosystems and biodiversity. Construction and operation of these facilities may lead to habitat loss, pollution, and other disturbances that negatively affect local wildlife and plant species.

12.5.7 Social acceptance

Social acceptance is a critical factor influencing the adoption and implementation of modern agricultural waste management technologies. Several social challenges limit the acceptance of these technologies, including:

Public perception and awareness: Many people lack awareness about the benefits and necessity of advanced agricultural waste management technologies. This lack of understanding can lead to resistance or indifference toward adopting

new systems. Public education campaigns are essential to inform communities about how these technologies can improve environmental sustainability and public health.

Cultural attitudes and practices: In many rural and agricultural communities, traditional practices are deeply ingrained. Introducing modern waste management technologies can be seen as disruptive to established routines and cultural norms. This resistance to change can hinder the acceptance and implementation of new technologies.

Economic concerns: The high initial costs and potential financial risks associated with implementing new technologies can be a deterrent. Farmers and local communities may be reluctant to invest in or support technologies that require significant financial outlay, especially when the economic benefits are not immediately apparent.

Policy and regulatory support: The level of governmental support and favorable policies significantly impact social acceptance. Policies that provide subsidies, incentives, or technical support can enhance acceptance by reducing the financial burden and perceived risks associated with new technologies.

Trust and credibility: Trust in the institutions promoting and managing waste management technologies is crucial. Past failures, lack of transparency, or inadequate community engagement can lead to skepticism and resistance. Building trust through consistent and transparent communication and involving communities in decision-making can improve acceptance.

Addressing these social acceptance challenges requires comprehensive strategies, including education and outreach programs, community involvement, supportive policies, and efforts to build trust and demonstrate the tangible benefits of advanced waste management technologies.

12.6 Integration of traditional and modern approaches

12.6.1 Environmental impact assessment

Environmental impact assessment (EIA) is crucial in evaluating the potential environmental consequences of proposed projects or developments. Integrating traditional and modern approaches enhances the comprehensiveness and effectiveness of EIAs (Petts, 2009). Traditional approaches involve indigenous knowledge, cultural practices, and community insights, while modern approaches utilize scientific methodologies and technological advancements (Usher, 2000). Combining these two approaches allows EIAs to address diverse environmental concerns better and ensure sustainable development.

Traditional knowledge offers valuable insights into local ecosystems, biodiversity, and resource management practices. Indigenous communities possess deep-rooted wisdom about their environment, including seasonal changes, habitat preferences of wildlife, and sustainable harvesting techniques. Incorporating this knowledge into EIAs fosters a deeper understanding of ecosystem dynamics and helps identify potential impacts that may be overlooked by purely scientific assessments (Duffy and Tschirley, 2000).

On the other hand, modern approaches provide systematic frameworks, data-driven analysis, and predictive modeling tools to assess environmental impacts accurately. Techniques such as geographic information systems (GIS), remote sensing, and computer simulations enable precise mapping of environmental features, forecasting of ecological changes, and simulation of project impacts under different scenarios. These methods enhance the rigor and objectivity of EIAs, facilitating informed decision-making and mitigation strategies.

Integrating traditional and modern approaches in EIAs promotes a holistic understanding of environmental issues and fosters collaboration between diverse stakeholders (David, 2005). It acknowledges the significance of indigenous perspectives while harnessing the benefits of scientific expertise. This interdisciplinary approach improves the accuracy of impact predictions and enhances the legitimacy and acceptance of assessment outcomes within affected communities.

Integrating traditional and modern approaches enriches the Environmental Impact Assessment process by combining indigenous wisdom with scientific rigor. This synthesis leads to more comprehensive assessments and better-informed decisions, ultimately contributing to sustainable development.

12.6.2 Economic viability of integration

Integrating traditional and modern approaches in economics presents a nuanced perspective that acknowledges the value of time-tested methods alongside contemporary innovations. Achieving economic viability through this integration requires balancing efficiency, sustainability, and cultural relevance.

Traditional approaches, rooted in historical practices and indigenous knowledge, offer insights into local ecosystems, resource management, and community dynamics. For example, indigenous farming techniques often prioritize sustainability and resilience, aligning with modern calls for environmentally friendly practices (Murry and Lalruatsangi, 2019). By incorporating such methods, economic systems can enhance long-term viability while respecting cultural heritage.

On the other hand, modern approaches leverage technological advancements, data analytics, and global market insights to optimize productivity and competitiveness. These methods emphasize efficiency and scalability, driving economic growth and development. Integrating modern tools with traditional practices can improve productivity without compromising sustainability, fostering inclusive economic progress.

Moreover, blending traditional wisdom with modern strategies fosters social cohesion and resilience. Local communities feel empowered when their cultural practices are recognized and integrated into economic initiatives, leading to greater participation and ownership. This approach fosters inclusive development, as marginalized groups benefit from preserving and leveraging their cultural heritage.

The economic viability of integrating traditional and modern approaches lies in harnessing both paradigms' strengths while mitigating their weaknesses. By combining indigenous knowledge with contemporary tools, economies can achieve sustainable growth, foster social inclusion, and preserve cultural diversity.

12.6.3 Synergies and complementarities

Synergies and complementarities arise when traditional and modern approaches to agricultural waste management are integrated. Traditional methods, rooted in indigenous knowledge and modern techniques driven by technological advancements, can effectively work together to address the multifaceted challenges of agricultural waste management. Integrating traditional and modern approaches to agricultural waste management offers synergistic benefits and complementary advantages. This synergy fosters innovation, sustainability, and resilience in addressing waste management challenges in agricultural systems.

12.6.4 Technological integration for efficiency

Agricultural waste management is crucial for sustainable farming practices and environmental conservation. Integrating traditional and modern approaches can enhance efficiency and effectiveness in handling agricultural waste. This integration relies on leveraging technology to streamline processes and maximize resource utilization.

Farmers have long employed traditional methods such as composting, mulching, and crop rotation to manage agricultural waste (Sekhar *et al.*, 2024). These methods promote soil health, reduce erosion, and recycle nutrients into the ecosystem. However, they often lack precision and scalability, leading to inefficiencies in large-scale agricultural operations.

Modern approaches, on the other hand, encompass advanced technologies like bioreactors, anaerobic digesters, and biomass conversion systems. These technologies offer higher efficiency, faster decomposition rates, and the potential for energy generation through biofuel production or biogas capture. However, their adoption may be limited by high initial costs and technical expertise requirements.

Farmers can capitalize on each method's strengths by integrating traditional and modern approaches while mitigating their weaknesses (Smith *et al.*, 2007). For instance, combining composting with bioreactor technology allows for faster decomposition while maintaining the organic integrity of the compost. Similarly, precision agriculture techniques like remote sensing and data analytics can optimize waste management strategies by identifying areas of high nutrient accumulation or soil erosion.

12.6.5 Knowledge transfer and capacity building

Knowledge transfer and capacity building are essential components of integrating traditional and modern approaches to agricultural waste management (Hatcheu, 2019). This process involves exchanging information, skills, and practices between different stakeholders to enhance their understanding and ability to manage agricultural waste effectively.

Traditional approaches often encompass age-old practices and indigenous knowledge passed down through generations (Murry and Lalruatsangi, 2019). These methods are deeply rooted in local cultures and have been adapted to suit the specific needs of communities over time. On the other hand, modern approaches leverage scientific advancements, technologies, and innovative techniques to address contemporary challenges in waste management (Rajput *et al.*, 2023).

By integrating traditional and modern approaches, there is an opportunity to harness the strengths of both systems. Traditional knowledge provides insights into sustainable practices and resource management techniques, while modern approaches offer scientific rigor and waste treatment and disposal efficiency.

Knowledge transfer involves sharing traditional wisdom with modern practitioners and vice versa. This exchange facilitates a deeper understanding of the cultural, environmental, and socioeconomic contexts surrounding agricultural waste management (Hatcheu, 2019). Capacity-building activities, such as workshops, training programs, and collaborative projects, empower individuals and communities to adopt integrated approaches effectively.

12.7 Technological innovations in agricultural waste management

12.7.1 Precision agriculture technologies

Precision agriculture technologies have significantly advanced the field of agricultural waste management through technological innovations. Precision agriculture uses technology to monitor and manage crop production, ensuring optimal growth conditions and minimizing waste (Gebbers and Adamchuk, 2010). Key technologies in this field include GPS-guided machinery, remote sensing, drones, and data analytics. By integrating these technologies, precision agriculture enhances the efficiency of agricultural practices, reducing waste generation and promoting sustainable farming (Mulla, 2013). The targeted application of inputs conserves resources and mitigates environmental impacts, contributing to better agricultural waste management.

12.7.2 Bioenergy production from agricultural waste

Bioenergy production from agricultural waste represents a significant advancement in sustainable energy solutions, effectively transforming what was once considered waste into a valuable resource (Angelidaki and Ellegaard, 2003). This process mitigates the environmental impact of agricultural residues and provides a renewable source of energy, contributing to energy security and reducing reliance on fossil fuels. Technological innovations in bioenergy production from agricultural waste include but are not limited to anaerobic digestion, thermochemical conversion, enzymatic hydrolysis and fermentation, and advanced pretreatment technologies, integrated biorefineries (Sun and Cheng, 2002).

Technological innovations in converting agricultural waste into bioenergy provide sustainable energy solutions and contribute to effective waste management and environmental conservation. Continuous research and development in this field are essential to enhance further these technologies' efficiency, scalability, and economic feasibility.

12.7.3 Innovative crop residue management

Innovative crop residue management involves using advanced technologies and methods to handle agricultural waste effectively, addressing environmental concerns, and maximizing resource efficiency (Kumar *et al.*, 2024). Kumar *et al.* (2020) in their work stated some approaches to innovative crop residue management:

Mechanized harvesting and processing: Technologies such as combine harvesters equipped with choppers and spreaders help cut and evenly distribute crop residues, facilitating easier subsequent management.
Biochemical processes: Techniques like anaerobic digestion and composting utilize microorganisms to break down residues, producing biogas or nutrient-rich compost as byproducts.
Bioenergy production: Crop residues can be converted into biofuels like bioethanol or biomass pellets through thermochemical processes such as pyrolysis and gasification.
Soil incorporation: Directly incorporating residues into the soil through no-till farming enhances soil organic matter content, improves fertility, and reduces erosion.
Remote sensing and precision agriculture: Satellite imagery and drones enable precise monitoring of crop residues, guiding their management and utilization decisions.
Government policies and incentives: Supportive policies promoting sustainable residue management practices encourage the adoption of innovative technologies among farmers.

The innovations above mitigate environmental impact and offer economic opportunities through value-added products derived from agricultural waste, contributing to sustainable development in the agricultural sector.

12.7.4 Biological approaches to waste decomposition

Biological approaches to waste decomposition play a crucial role in technological innovations for agricultural waste management, offering sustainable solutions that minimize environmental impact and enhance resource efficiency (Bernal, Alburquerque, and Moral, 2009). Biological waste decomposition approaches include composting, anaerobic digestion, microbial inoculants, and enzymatic technology. A growing understanding of microbial ecology, genetic engineering, and bioprocess optimization drives technological innovations in biological waste decomposition. These approaches help manage agricultural waste more effectively and contribute to sustainable agriculture by reducing greenhouse gas emissions, conserving water, and improving soil health.

12.7.5 Robotics and automation in waste handling

Technological innovations in agricultural waste management have increasingly integrated robotics and automation to enhance efficiency and sustainability in waste-handling processes. Robotics in waste handling involves automated systems for sorting, recycling, and disposing of agricultural waste materials such as crop residues, packaging materials, and organic waste (Satav *et al.*, 2023). In recent times, essential advancements have evolved in robotics and automation in waste handling, including automated sorting systems, smart waste collection, processing and recycling, and data-driven management. These innovations enhance operational efficiency and contribute significantly to reducing environmental impact and promoting sustainable agricultural practices.

12.7.6 Government policies and regulatory frameworks

The Organisation for Economic Co-operation and Development (OECD) provides that government policies and regulatory frameworks play a crucial role in adopting and implementing technological innovations in agricultural waste management. These policies aim to promote sustainability, reduce environmental impact, and ensure compliance with waste management standards. The overview of some government policies and regulatory frameworks described by *Agricultural Policy Monitoring and Evaluation 2021: Addressing the Challenges Facing Food Systems* (2021) is discussed below.

Regulatory standards: Governments establish regulations that define permissible waste disposal methods, recycling requirements, and environmental impact assessments. These standards ensure that technological innovations in waste management meet legal and environmental criteria.
Financial incentives: Governments often provide financial incentives such as grants, subsidies, or tax credits to encourage the adoption of innovative waste management technologies. These incentives lower financial barriers and promote investment in sustainable practices.
Research and development support: Policies may support research and development initiatives to advance technologies for agricultural waste management. This support fosters innovation and drives the development of new solutions.
Collaboration and partnerships: Governments facilitate collaboration between industry stakeholders, research institutions, and technology developers to accelerate the adoption of innovative waste management technologies. This cooperation enhances knowledge sharing and promotes best practices.
Monitoring and enforcement: Regulatory bodies monitor compliance with waste management regulations and enforce penalties for noncompliance. This ensures that technological innovations are implemented responsibly and effectively.

These policies and frameworks create a supportive environment for technological innovations in agricultural waste management, fostering sustainable practices and addressing environmental challenges effectively.

12.8 Conclusion

In conclusion, exploring traditional and modern waste management technologies underscores progress and persistent challenges in addressing waste. While modern technologies offer promising solutions such as recycling, composting, and advanced waste-to-energy systems, they come with limitations, including high initial costs, technological complexities, and environmental concerns. Meanwhile, traditional methods like landfilling and incineration continue to play a significant role in waste management but face criticism due to their negative impacts on the environment and public health. Navigating the complexities of waste management requires a balanced approach that harnesses the benefits of modern technologies while acknowledging and mitigating their limitations. Moreover, it demands a concerted effort to integrate traditional practices with innovative solutions, considering local contexts and community needs. Collaboration among governments, industries, communities, and environmental advocates is essential to overcome the challenges ahead. By prioritizing sustainability, efficiency, and inclusivity, we can strive toward a future where waste is managed responsibly, safeguarding human health and the environment for future generations.

AI Disclosure

During the preparation of this work, the author(s) used QuillBot in order to rework some sentences and check grammatical errors. The author(s) therefore take(s) full responsibility for the publication of this book's content. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Chapter 13

Integrated waste management systems: Holistic approaches to waste management in agriculture

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Chapter Outline

13.1. Introduction 203
13.2. Importance of integrated waste management systems (IWMS) 204
13.3. Environmental and economic impacts of agricultural waste 205
13.4. Biological treatment methods 206
13.5. Chemical treatment methods 207
13.6. Combined and integrated approaches 208
13.7. Chemical precipitation 210
13.8. Physical treatment methods 211
13.9. Conclusion 212
References 213

13.1 Introduction

Agriculture contributes remarkably to the evolution of human civilization. The production of livestock and cultivation of plants provides secure food and permits the ancient human communities to live in a particular place and establish socioeconomic and cultural organization (Till, 2022). The transformation of agriculture and its widespread effect has fostered trade, supported the growth of the population, and finally shaped the global economic status. Higher population growth created massive pressure on agriculture to fulfill the demand for food security (Duque-Acevedo *et al.*, 2020). Global agriculture production has reached up to 23.7 million tons of food daily; this excessive population growth has caused environmental deterioration and jeopardized the soil, air, water resources ecosystem, and human health. This speedy increase in agricultural production has raised a significantly higher growth in waste production, creating ecological and economic concerns.

"Agro-waste" comprises waste from various agricultural practices (Thangadurai *et al.*, 2021). These results have emerged from farm practices but are not used in producing or processing primary agricultural products. However, some agro-waste has some valuable components, but their economic value falls due to the lack of expenses associated with the collection, transportation, and processing. As a result, agricultural waste and byproducts are frequently thrown away because they are considered unprofitable. Although accurate estimates of the amount of agro-waste produced are still challenging, it is widely accepted that agro-waste plays a significant role in creating garbage worldwide (Agamuthu, 2009).

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If appropriate action is not taken, this condition may get worse. The imperative to tackle waste management issues and utilize cutting-edge engineering methods to transform agro-industrial waste into valuable commodities has put a crucial emphasis on obtaining value from this trash.

The present chapter has been designed to summarize the integrative waste management strategies for the conversion of waste materials into useful products such as vermicompost, biogas, biodiesel, biofuels, bioinsecticide, herbal dyes, and herbal incense sticks. Various methods for the management of different types of waste, viz. biological, chemical, and physical, have also been discussed.

13.2 Importance of integrated waste management systems (IWMS)

An integrated waste management system (IWMS) is essential for effectively managing agricultural waste and obtaining various environmental, economic, and health benefits. Implementation of IWMS helps us to divert agricultural waste from landfills into valuable products that could help us to reduce the emission of methane, a significant greenhouse gas, and prevent the contamination of water due to pesticides, fertilizers, and organic matter coming with the runoff (Hajam, Kumar, and Kumar, 2023). In addition to this, IWMS helps to enhance the rate of resource recovery and recycling through composting organic waste into nutrient-rich soil that helps to amend the fertility of the soil and helps in the minimum use of chemical fertilizers and conversion of agricultural waste into renewable bioenergy sources such as biogas or biofuels (Phiri, Mavinkere Rangappa, and Siengchin, 2024). IWMS is also economically viable because it saves costs by decreasing waste disposal expenses and producing value-added products. Moreover, new jobs can be created in rural areas by developing waste management and recycling industries. IWMS helps to increase soil health by recycling nutrients and improving the structure of the soil, which in turn results in the retention of water and aeration of soil. Mitigation of climate change is another critical benefit of following the IWMS, which is the reduction of greenhouse gases from the decomposition of waste and the facilitation of carbon sequestration in the soil through organic amendment and biochar. IWMS could also be beneficial for promoting a circular economy and reducing dependency on external inputs, and it also supports sustainable agricultural practices and increases farm resilience (Hajam, Kumar, and Neelam, 2024). In addition, efficient IWMS decreases the risks to public health by controlling pests and pathogens; it also ensures the proper and safe disposal of hazardous agricultural waste, including pesticide containers. Hence, integration of the waste management practices used for the transformation of farm waste and other biodegradable wastes, such as temple waste, into valuable resources could help to optimize/balance the environmental and economic concerns by promoting sustainability and resilience in the agricultural system (Kumar *et al.*, 2024) (Figure 13.1).

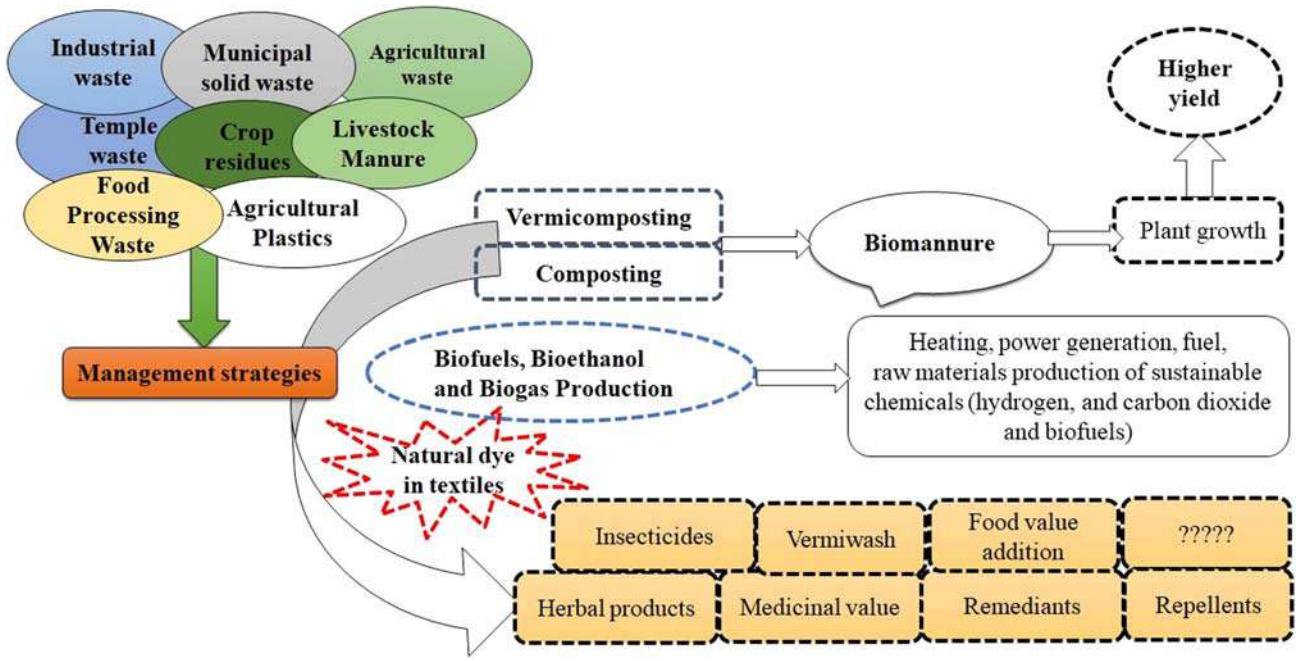


FIGURE 13.1 **Depicts the management of different types of waste and their conversion into valuable products for sustainability.**

13.3 Environmental and economic impacts of agricultural waste

Agricultural waste includes crop residues, animal dung, agrarian plastics, and trash from food processing, which significantly affects the environment and the economy. It is necessary to address the impact of these problems, which require a comprehensive understanding of how these waste streams affect ecosystems, resource utilization, and economic activities.

13.3.1 Environmental impacts

13.3.1.1 Crop residues

Crop residues (straw, stalks, husks, and leaves), if not properly managed, can contribute to air pollution by burning them openly, which emits particulate matter and greenhouse gases such as carbon dioxide and methane (Mathur and Srivastava, 2019). This activity adds to climate change and worsens the quality of the air. On the other hand, leaving residues in fields without adequate management can lead to pest and disease outbreaks, affecting subsequent crops. However, crop leftovers can improve soil health by adding organic matter, enhancing soil structure, and reducing erosion to soil when utilized effectively (Table 13.1).

13.3.1.2 Livestock manure

Livestock manure is a valuable resource as organic fertilizer, but improper handling can have adverse environmental effects. Excessive application can lead to nutrient runoff that contaminates water bodies with phosphates and nitrates, which can cause eutrophication and toxic algal blooms (Khan and Mohammad, 2014). Moreover, the decomposition of manure releases two potent greenhouse gases, nitrous oxide and methane, that contribute to global warming (Thangadurai *et al.*, 2021). Proper management techniques, such as anaerobic digestion and composting, can lessen these effects by stabilizing nutrients and storing methane for energy production.

13.3.1.3 Agricultural plastics

Agricultural plastics, such as mulch films, greenhouse covers, and silage bags, are necessary for modern farming and can cause significant environmental challenges (Briassoulis, 2023). Inadequate disposal practices can cause plastic contamination in soil and water bodies, harming wildlife and disrupting ecosystems. Microplastics originate from degraded agricultural plastics and can accumulate in the food chain, posing risks to human health. Environmental impacts of farming plastics can be minimized by recycling and utilizing biodegradable substitutes.

TABLE 13.1 Summarizes the various types of agricultural waste, their sources, and their economic importance.

Agricultural waste	Source	Types	Economic importance
Crop Residues	Crop production	Straw Stalks Husks Leaves	Biofuel production: Used in biomass energy plants. Soil amendment: Enhances soil fertility and structure. Animal feed: Alternative feed source for livestock.
Livestock Manure	Livestock farming	Cattle manure Poultry manure Swine manure	Organic fertilizer: Improves soil health and crop yield. Biogas production: Used in anaerobic digestion to produce methane for energy. Soil amendment: Enhances soil fertility.
Agricultural Plastics	Agricultural activities	Mulch films Greenhouse covers Silage bags	Recycling: Can be processed into new plastic products. Energy recovery: Can be used as fuel in certain waste-to-energy plants. Cost savings: Reduces the need for new plastic production.
Food Processing Waste	Food processing industries	Fruit peels Vegetable trimmings Meat offcuts Dairy byproducts	Animal feed: Provides a nutrient-rich feed for livestock. Composting: Converts waste into valuable compost for soil amendment. Biogas production: Used in anaerobic digestion for energy.

13.3.1.4 Food processing waste

Food processing waste, which includes fruit peels, vegetable trimmings, meat offcuts, and dairy byproducts, if managed improperly, can lead to landfill overloading and methane production from anaerobic decomposition (Mena and Whitehead, 2008). For proper management, this waste can be kept out of landfills and used in biogas, composting, or animal feed, which minimizes the adverse impacts of waste on the environment (Ayilara *et al.*, 2020). Anaerobic digestion and composting provide beneficial soil nutrients and renewable energy in addition to reducing greenhouse gas emissions.

13.4 Biological treatment methods

13.4.1 Composting

Composting is a natural process of biotransformation that converts organic waste into stable and nutrient-rich manure, which is free from any toxicants. The word "compost" is derived from the Latin word *component,* which means to put together (Figure 13.2). Composting is an economical and environmentally friendly method for managing various types of waste, such as animal manure, industrial waste, crop straws, and municipal solid waste (Sayara *et al.*, 2020). The process of composting involves depositing organic materials in containers and allowing them to decompose through the action of microorganisms, such as bacteria and fungi (Diksha and Kumar, 2022; Kumar, Nandi, and Pakshirajan, 2021). The waste composition of developing countries, which often contains high moisture content, makes composting a suitable method for the management of municipal solid waste (Sayara *et al.*, 2020). This method is commonly used to convert organic waste into organic manure (compost), which recycles mineral nutrients such as nitrogen, phosphorus, and potassium, making it suitable for agricultural practices (Ahmad *et al.*, 2022; Mupambwa and Mnkeni, 2018).

Composting under thermophilic conditions provides hygienic compost by destroying pathogenic organisms within the waste. The high temperatures required for the thermophilic phase of composting are optimal for the degradation of lignin in compost. Moreover, during composting, decomposition and humification lead to the production of humic acid and humic-like substances, which can be used for soil remediation and heavy metal immobilization.

In addition, composting is an environmentally friendly approach to managing organic waste, as it can help remove large quantities of toxicants, pollutants, plastic molecules, and residues and have a positive impact on the biotic community, including biodegrading microorganisms and soil-dwelling animals, such as earthworms. During the initial phase, microorganisms decompose soluble organic compounds (starch and lipids), followed by proteins (Marschner, Umar, and Baumann, 2011). Some highly resistant compounds, such as cellulose, hemicellulose, and lignin, are partially degraded and converted into humus (Lou *et al.*, 2022). The pH of the composting material also changes during the process, with an initial decrease due to the production of organic acids from the breakdown of starch and lipids, followed by an increase as the microorganisms degrade proteins (Zhang *et al.*, 2020).

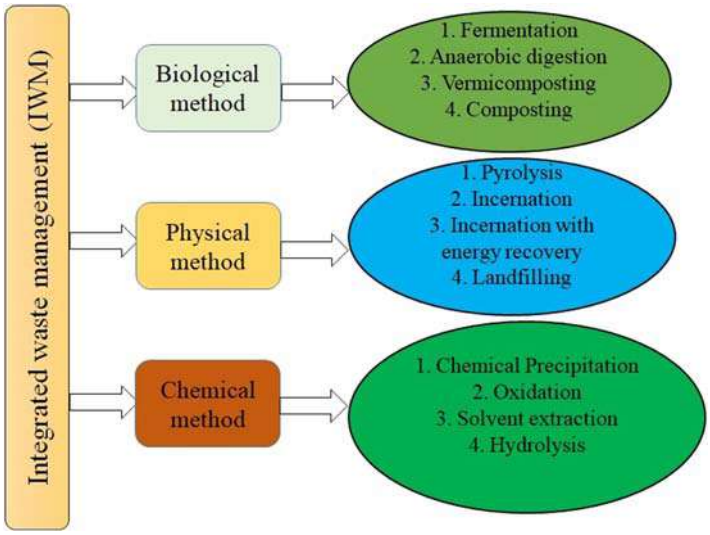


FIGURE 13.2 Diagram depicting the different waste management methods (biological, physical, and chemical). Different waste management methods including biological methods, physical methods, and chemical methods.

13.4.2 Anaerobic digestion

Anaerobic digestion is a biological procedure that breaks down organic material without oxygen to create biogas and digestate. Recent literature has shown great interest in this technology for its potential to produce renewable energy, manage waste, and provide environmental advantages (Figure 13.2). AD is being more and more acknowledged for its contribution to tackling worldwide issues concerning energy security, waste disposal, and climate change mitigation (Wu *et al.*, 2019).

Advances in anaerobic digestion technology in recent times have improved its effectiveness and usability. Advancements in digester technology have enhanced the efficiency and reliability of the process. Newer anaerobic digesters, such as CSTRs, UASBs, and AnMBRs, create ideal environments for microbes, resulting in increased biogas production and improved waste breakdown. Advancements in pretreatment methods have also played a key role in enhancing the effectiveness of anaerobic digestion. Techniques such as thermal hydrolysis, mechanical disruption, and chemical treatments degrade complex organic substances into simpler compounds, improving their accessibility to anaerobic microbes. The pretreatment procedures improve the general biodegradability of raw materials, leading to higher biogas generation.

The variety of feedstocks appropriate for anaerobic digestion has increased, increasing the versatility of the technology. Common sources for feedstocks are remnants from farming, animal waste, and leftover meals. Nevertheless, recent research has investigated the possibilities of using industrial waste like brewery waste and dairy byproducts, sewage sludge, and organic parts of municipal solid waste. This diversification not only offers a sustainable waste management solution but also enhances resource recovery from different waste streams. Co-digestion, which involves digesting multiple feedstocks at the same time, has become a promising method. Mixing various forms of natural waste can help regulate nutrient levels, boost microbial function, and increase biogas production. For example, blending food waste with livestock manure can balance out the elevated nitrogen levels in manure, avoiding ammonia inhibition and enhancing the digestion process (Chodkowska-Miszczuk, Martinát, and van der Horst, 2021).

Anaerobic digestion provides significant environmental advantages, making it an essential part of sustainable waste management and renewable energy plans. Decreasing greenhouse gas emissions is among the most important benefits. By capturing methane from organic matter decomposition, AD stops it from being released into the atmosphere and causing climate change. Instead, biogas is produced from methane, serving as a renewable energy source for heating, generating electricity, or powering vehicles. Another important advantage is nutrient recycling. The nutrient-rich digestate is a byproduct of anaerobic digestion and contains nitrogen, phosphorus, and potassium. This turns it into a great natural fertilizer, improving soil quality and decreasing reliance on synthetic fertilizers. Utilizing digestate in farming promotes sustainable practices and aids in closing nutrient loops (Breitenmoser *et al.*, 2019).

The economic consequences of anaerobic digestion are complex. AD can lead to substantial cost reductions in waste management by decreasing the need for landfills and the corresponding disposal charges. AD has the potential to generate additional income for municipalities, farmers, and industries by turning waste into valuable biogas and digestible products.

There are profitable opportunities to utilize biogas as a renewable energy source. Biogas can be refined into biomethane and added to natural gas pipelines or compressed for transportation fuel, entering the increasing demand for sustainable energy. Moreover, the selling of carbon credits generated from decreased methane emissions can offer additional financial motivation (Kabeyi, Olanrewaju, and Messineo, 2022).

Policy and regulations are important in promoting and growing anaerobic digestion. Governments around the globe acknowledge the advantages of AD and are enacting supportive measures to encourage its adoption. Incentives such as feed-in tariffs, renewable energy certificates, and subsidies for AD infrastructure are driving investment in anaerobic digestion projects. The incorporation of anaerobic digestion into circular economy strategies is becoming increasingly popular. AD aligns with the circular economy principles by considering waste a valuable resource, encouraging sustainable resource utilization, and reducing waste. Support from national and regional policies for circular economy initiatives is expected to enhance the acceptance of anaerobic digestion (Edwards, Othman, and Burn, 2015).

Anaerobic digestion is a flexible and eco-friendly technology that has great promise for producing renewable energy, managing waste, and safeguarding the environment. Advances in technology, the use of different feedstocks, and support from policies have improved effectiveness and versatility. Anaerobic digestion is seen as a hopeful solution amid global concerns about energy security, waste management, and climate change, offering a way to build a more sustainable and resilient future (Ziolkowska, 2020).

13.5 Chemical treatment methods

Chemical treatment techniques for agricultural waste recycling have become a focal point in recent studies for their ability to transform waste into valuable resources. These techniques utilize chemicals and procedures to break down complex

organic substances, improve their ability to be broken down by living organisms, and make it easier to recover valuable resources. Hydrolysis, oxidation, and solvent extraction are the main chemical treatment methods used in agricultural waste recycling, each with its benefits and uses (Awaleh, 2014).

13.5.1 Hydrolysis

Hydrolysis is a commonly researched chemical process used to break down agricultural waste into more basic compounds. This method includes adding acids, alkalis, or enzymes to decompose complex carbohydrates, proteins, and fats. Strong acids such as sulfuric or hydrochloric acid are used in acid hydrolysis to transform lignocellulosic materials into sugars that can be fermented. Recent developments have concentrated on enhancing reaction parameters to increase sugar production while reducing the creation of substances that could impact subsequent fermentation stages. Utilizing substances such as sodium hydroxide in alkaline hydrolysis proves to be efficient in removing lignin from biomass, thereby enhancing the accessibility of cellulose and hemicellulose for subsequent procedures. Enzymatic hydrolysis employs particular enzymes to specifically target and break down polysaccharides into simple sugars in gentler conditions, maintaining the integrity of important compounds (Prado *et al.*, 2016).

13.5.2 Oxidation

Oxidation procedures utilize chemical oxidants to decompose organic material in agricultural waste. Fenton's solution, comprising hydrogen peroxide and iron salts, is a leading technique for managing organic waste because it can produce hydroxyl radicals, which are capable of breaking down various organic contaminants. Current studies have investigated how Fenton's reagent can improve the digestibility of lignocellulosic biomass before anaerobic digestion or bioethanol production. Another oxidation method called ozonation involves utilizing ozone gas to oxidize organic substances, resulting in the decomposition of intricate molecules and the decrease of resistant materials. The biodegradability of agricultural residues can be enhanced by ozonation, making them suitable for biogas production and composting (Wei *et al.*, 2017).

13.5.3 Solvent extraction

Solvent extraction is the process of using solvents to dissolve and extract specific components from agricultural waste. This technique is especially beneficial for extracting valuable bioactive compounds, oils, and other high-value chemicals. Supercritical CO_2 extraction, known as SFE, is a developing method with benefits like high selectivity, minimal toxicity, and the ability to work at lower temperatures. Recent research has shown that SFE is efficient in obtaining essential oils, antioxidants, and other beneficial substances from agricultural byproducts like fruit peels, seeds, and leaves. Ionic liquids (ILs) are becoming increasingly popular as solvents due to their capacity to dissolve lignocellulosic biomass. ILs can break down the lignin structure, making it easier to extract cellulose and hemicellulose for the production of biofuels and biochemicals (Van Osch *et al.*, 2017).

13.6 Combined and integrated approaches

Recent studies emphasize the advantages of integrating chemical treatment methods with additional pretreatment and processing techniques to improve the effectiveness and yield of agricultural waste recycling. Combining acid hydrolysis with enzymatic hydrolysis can greatly enhance the overall conversion efficiency of lignocellulosic biomass by integrating chemical and biological treatments. Combining physical pretreatments such as milling or ultrasonication with chemical treatments in hybrid processes has displayed the potential to improve the accessibility and reactivity of agricultural waste as well (Awaleh, 2014).

13.6.1 Environmental and economic considerations

While chemical treatment methods offer significant advantages in the recycling of agricultural waste, their environmental and economic impacts must be carefully considered. The use of strong acids and alkalis can generate hazardous waste streams that require proper management and disposal. Advances in green chemistry aim to develop more sustainable and less toxic chemical agents and processes. The economic feasibility of these methods depends on factors such as the cost of chemicals, energy requirements, and the value of the recovered products. Lifecycle assessments and techno-economic analyses are essential tools for evaluating the overall sustainability and economic viability of chemical treatment methods in agricultural waste recycling (Mahmud *et al.*, 2021).

Chemical treatment techniques are essential in the recycling of agricultural waste, providing effective ways to turn waste into valuable products. Progress in hydrolysis, oxidation, and solvent extraction techniques has broadened the variety of raw materials and uses, improving the overall effectiveness of waste recycling methods. Despite continued environmental and economic obstacles, advancements in green chemistry and integrated strategies offer the potential to make chemical processes more sustainable and profitable. With the increased focus on promoting sustainable waste management and resource recovery worldwide, chemical treatment methods will remain crucial for innovating and applying recycling techniques to agricultural waste (Mahmud *et al.*, 2021).

13.6.2 Fermentation

Fermentation plays a crucial role in the reusing and control of agricultural waste, providing an effective way to transform organic leftovers into useful items like biofuels, biochemicals, and animal feed. Recent studies have been focusing on the progress and uses of fermentation technologies, underscoring their importance in sustainable waste treatment and the retrieval of resources (Chilakamarry *et al.*, 2022).

The utilization of fermentation in managing agricultural waste is most notably seen in the creation of bioethanol. Crop residues and forestry byproducts like corn stover and wheat straw are used as raw materials for producing bioethanol. Advancements in pretreatment technologies have improved the effectiveness of turning lignocellulosic materials into sugars that can be fermented. Methods like steam explosion, dilute acid hydrolysis, and enzymatic hydrolysis all work to convert complex polysaccharides into simple sugars, which can be fermented by microorganisms such as *Saccharomyces cerevisiae*. Genetically modifying fermenting microorganisms has enhanced their resistance to inhibitors and their capacity to ferment a wider variety of sugars, ultimately boosting bioethanol production (Walker and Stewart, 2016).

Anaerobic fermentation plays a crucial role in the generation of biogas. Livestock manure and crop residues are processed through anaerobic digestion by microorganisms without oxygen to create biogas, which is a mixture of methane and carbon dioxide. Recent research has concentrated on enhancing co-digestion approaches, in which various forms of waste are treated jointly to harmonize nutrient levels and enhance microbial function. This method improves biogas production and operational consistency, increasing the feasibility of using anaerobic digestion for agricultural waste management. Biobutanol, a different type of biofuel made from fermentation, is being recognized for its increased energy density and ability to work with current fuel systems, unlike bioethanol. *Clostridium* species are frequently employed in the ABE fermentation method to transform agricultural leftovers into biobutanol. Progress in metabolic engineering has allowed for the creation of strong microbial strains that can withstand higher levels of butanol and utilize a wider variety of substrates, enhancing overall production efficiency (Wang *et al.*, 2017).

Fermentation also aids in the generation of lactic acid, citric acid, and acetic acid from agricultural waste. These organic acids are used as starting materials for biodegradable plastics (bioplastics) and other industrial chemicals. For example, in lactic acid fermentation, bacteria such as *Lactobacillus* species are used to transform carbohydrate-rich agricultural leftovers into lactic acid. This procedure is essential in the manufacturing of polylactic acid (PLA), a compostable plastic used in packaging and textiles. Current studies are concentrating on improving fermentation conditions and increasing production processes to make bioplastics a more economically feasible option compared to traditional plastics (Swetha *et al.*, 2023).

Fermentation can improve the nutritional quality of agricultural waste, turning it into high-grade animal feed and nutraceuticals. Solid-state fermentation, involving fungi such as *Aspergillus* and *Trichoderma* species, can enhance agricultural residues by adding protein, vitamins, and enzymes, rendering them ideal for livestock feed. This not only offers a budget-friendly source of food but also diminishes the environmental consequences of waste removal. Moreover, fermentation can generate nutraceuticals, including antioxidants and probiotics, from leftover agricultural materials, aiding in the advancement of functional foods and dietary supplements (Yafetto, Odamtten, and Wiafe-Kwagyan, 2023).

The process of fermenting agricultural waste brings about important advantages for the environment and economy. Fermentation helps lessen climate change by diverting waste from landfills and decreasing methane emissions from decomposing organic matter. Creating biofuels and biochemicals from waste lessens dependence on fossil fuels, thereby encouraging a circular economy. From an economic perspective, fermentation turns inexpensive raw materials into higher-value products, offering additional income sources to farmers and waste management firms. Additionally, decentralized fermentation facilities can boost rural economies by generating employment opportunities and backing local businesses.

Even with its promising possibilities, the process of fermenting agricultural waste for recycling encounters numerous obstacles. Differences in waste makeup and varying seasonal availability can impact the efficiency of processes and the number of products produced. Ongoing research is being conducted to create strong strains of microbes and flexible fermentation methods capable of processing a variety of raw materials. Furthermore, combining fermentation with other

methods of waste management, like anaerobic digestion and composting, can improve the recovery of resources and boost sustainability as a whole. Fermentation is vital in the repurposing and control of agricultural waste, providing a sustainable method for transforming organic leftovers into useful goods. Recent improvements in fermentation technologies, along with continuous research and innovation, are expected to improve the effectiveness and expandability of these processes. As the world focuses more on sustainable waste management, fermentation will remain essential for moving toward a circular economy and a greener future.

13.7 Chemical precipitation

Chemical precipitation is a commonly studied technique for recycling and controlling agricultural waste, allowing for the retrieval of important nutrients and the mitigation of environmental contamination. Recent research emphasizes the progress made in chemical precipitation methods and their use in converting agricultural waste into valuable products.

Chemical precipitation is very efficient in extracting nutrients like phosphorus and nitrogen from agricultural waste. These important nutrients are necessary for the growth of plants and can be extracted from waste streams to create fertilizers. Struvite formation, consisting of magnesium ammonium phosphate, is a popular technique for phosphorus retrieval. By incorporating magnesium and regulating the pH of waste streams, phosphorus is transformed into struvite, a form of slow-release fertilizer. Recent developments have improved the process of struvite precipitation by investigating different sources of magnesium, such as seawater or waste from industries, to cut down expenses and improve eco-friendliness (Siciliano *et al.*, 2020).

Agricultural waste frequently holds heavy metals, presenting notable dangers to the environment and public health. Chemical precipitation can efficiently eliminate these pollutants, rendering the treated wastewater suitable for either reuse or disposal. Sulfide precipitation is the process of introducing sulfide compounds into waste streams, causing a reaction with heavy metals to create metal sulfides that are not soluble (Figure 13.2). This technique has been proven to effectively eliminate metals like cadmium, lead, and mercury from agricultural wastewater. Current studies aim to enhance the specificity and productivity of sulfide formation by utilizing new sulfide suppliers and refined reaction circumstances (Kumar, Nandi, and Pakshirajan, 2021).

Furthermore, agricultural waste can also include organic pollutants, such as pesticides and pharmaceuticals, alongside heavy metals. Recent research has indicated potential in co-precipitation methods, which involve the removal of organic pollutants alongside other precipitated substances. By choosing the right coagulants and adjusting precipitation conditions, organic pollutants can be efficiently adsorbed onto precipitated solids, making their elimination easier. This method improves the overall quality of processed agricultural waste, ensuring its safety for future uses.

Chemical precipitation is employed in treating agricultural wastewater to enhance its quality and allow for its reuse. Lime precipitation is frequently used to eliminate suspended solids, organic matter, and nutrients from wastewater. The pH is raised by adding lime, which leads to the formation of calcium carbonate and other substances that capture pollutants. This procedure not only purifies the sewage but also generates sludge that can be processed additionally or utilized as a soil amendment. Recent developments in lime precipitation have shifted toward decreasing sludge size and improving the effectiveness of removing contaminants by incorporating hybrid systems that integrate lime precipitation with other treatment techniques like coagulation and flocculation (Madeira *et al.*, 2023).

Although it is effective, chemical precipitation is faced with several challenges, such as handling precipitated sludge and ensuring accurate control of reaction conditions. The critical issue still at hand is the disposal or recycling of sludge, which may be packed with concentrated contaminants. Advancements in sludge management focus on transforming sludge into useful products like building materials or soil enhancers, cutting down on disposal expenses and environmental harm. The introduction of intelligent precipitation systems, which employ sensors and automation to enhance precipitation reactions instantly, is a breakthrough in the industry. These systems can modify chemical doses and reaction conditions according to live data, guaranteeing peak performance and minimizing chemical usage (Seleiman, Santanen, and Mäkelä, 2020).

Chemical precipitation provides significant advantages in terms of both cost and environmental impact. By extracting nutrients and eliminating contaminants, agricultural waste is converted into valuable resources, reducing reliance on synthetic fertilizers and addressing environmental pollution. Creating top-notch fertilizers from waste streams is essential for sustainable farming practices and advancing circular economy concepts. Furthermore, enhanced chemical precipitation in wastewater treatment helps decrease water pollution, safeguarding both aquatic ecosystems and public health. Chemical precipitation is a flexible and efficient technique for the reuse and control of agricultural waste. Recent developments have increased its effectiveness and expanded its uses, establishing it as a crucial technology in sustainable waste management. As research progresses in tackling challenges and improving processes, chemical precipitation will

become more crucial in converting agricultural waste into valuable resources, aiding in environmental protection and economic sustainability.

13.8 Physical treatment methods

13.8.1 Pyrolysis

Pyrolysis, a cutting-edge thermal treatment method, has been receiving much interest in recent publications due to its promise in repurposing and controlling agricultural waste. This method includes the heating of organic substances at high temperatures (usually ranging from 300°C to 700°C) without oxygen, leading to the creation of biochar, bio-oil, and syngas. All of these items provide useful functions that help with eco-friendly waste disposal and reclaiming resources.

Biochar is a stable carbon-rich material produced from pyrolysis that is commonly used to improve soil quality. Recent research has brought attention to the ability of biochar to boost soil fertility, enhance water retention, and store carbon, ultimately helping to reduce the impact of climate change. Extensive research has been conducted on utilizing agricultural residues like rice husks, corn stover, and sugarcane bagasse for pyrolysis. Studies show that biochar characteristics like surface area, pH, and nutrient content can be customized by changing pyrolysis factors such as temperature and heating rate. Biochar's adaptability enables it to be tailored for particular soil varieties and crop needs, rendering it a beneficial resource in eco-friendly farming (Masud *et al.*, 2023).

Pyrolysis also generates bio-oil, a diverse blend of organic substances that can be refined to create fuels for transportation or used as a raw material in chemical processes. The latest developments in catalytic pyrolysis are centered on improving the quality and quantity of bio-oil through the use of catalysts that aid in breaking down complex biomass compounds into more valuable, simpler chemicals. This method enhances the economic feasibility of producing bio-oil and also decreases the creation of unwanted compounds that can impede its effectiveness as a fuel. Furthermore, syngas, which consists mostly of hydrogen and carbon monoxide, is created through pyrolysis and can be utilized for producing energy or for additional chemical production. The blending of pyrolysis and gasification methods is actively being studied to enhance energy recovery from agricultural waste (Ganesapillai *et al.*, 2023).

Utilizing pyrolysis in the management of agricultural waste provides substantial environmental advantages. By transforming waste into valuable substances, pyrolysis reduces the amount of waste disposed in landfills, thus minimizing the related greenhouse gas emissions and leachate issues. Moreover, this process can assist in controlling agricultural waste that might otherwise cause air pollution if it were to be burned in open fields. The carbon sequestration ability of biochar is important for reducing the carbon footprint of farming, locking carbon in a stable form for centuries.

The economic feasibility of utilizing pyrolysis for recycling agricultural waste is determined by factors such as the availability of feedstock, costs of processing, and demand in the market for the final products. Despite significant advancements in pyrolysis technologies, there are still challenges in scaling up operations and maintaining consistent feedstock quality. Recent writings highlight the significance of creating pyrolysis systems within specific locations to handle agricultural waste locally, which decreases transportation expenses and supports circular economy principles. Moreover, by incorporating pyrolysis with other waste management methods like anaerobic digestion or composting, integrated systems can improve resource recovery and sustainability.

Policy frameworks and regulatory support also play a role in the implementation of pyrolysis for recycling agricultural waste. Governments are starting to realize how crucial waste-to-energy technologies are for meeting sustainability targets and cutting down on greenhouse gas emissions. Encouraging research and development, offering financial incentives, and streamlining the commercialization process of pyrolysis technologies can greatly boost their implementation (Alan and Köker, 2023). Pyrolysis is a hopeful technology that can be used to recycle and manage agricultural waste, providing useful products like biochar, bio-oil, and syngas. Advancements in pyrolysis technology and optimization of the process have broadened its usefulness and economic feasibility, rendering it an appealing choice for eco-friendly waste disposal. As the world shifts toward more circular and sustainable agricultural methods, pyrolysis will be crucial in converting agricultural waste into valuable resources and addressing environmental issues linked to waste disposal.

13.8.2 Landfilling

In this method, waste is dumped in a selected area of land. It is the earliest and most popular method for disposing of waste. The basic purpose of landfilling is to avoid any contact between the waste and the natural ecosystem, particularly the groundwater. Municipal, agricultural, industrial, commercial, and even medical wastes are all disposed of in landfill sites. The increased number of landfills is mainly due to urbanization and population growth. The demand for manufactured goods increases as the population and urbanization rates rise. When demand increases, solid waste, particularly plastic

garbage, rises as well. The majority of the plastic items are dumped in landfills. Various studies have reported that people near the landfilling sites suffer from genetic disorders, cancer, and low birth weight (Sharma *et al.*, 2021). It is insufficient and unsafe for the environment and living things. Methane gas is produced as a result of the decomposition of biological substances. It is a highly harmful poisonous gas released from landfills. A significant portion of these landfill pollutants penetrate the soil and eventually wind up in freshwater. This consequence hurts human health and ranges from water pollution to the release of hazardous chemicals into the atmosphere. In addition to this, it is also responsible for causing lung and heart diseases. The quality of the soil directly deteriorates due to chemicals and toxic gases released from landfills (Figure 13.2).

There are various waste management methods such as landfill, incineration, pyrolysis, composting, anaerobic digestion, open dumping, waste compaction, plasma gasification, open burning, and source reduction; however, all have various drawbacks and also impose adverse effects on the environment, living beings, the economy, etc. Despite these alarming trends, current waste management practices predominantly rely on landfilling, accounting for over 75% of global waste disposal (Kumar and Agrawal, 2020). However, this method generates leachate, polluting both surface and groundwater. Moreover, solid waste decomposition contributes significantly to greenhouse gas emissions, including methane, exacerbating climate change. Nevertheless, every constituent of solid waste holds potential utility if transformed into functional products through scientifically sound processes. Yet, improper waste management persists as a pervasive global issue, with open dumping practices widespread and over 3.5 billion people lacking awareness of proper waste disposal methods (Ferronato and Torretta, 2019). Consequently, an estimated 1.3 billion tons of municipal solid waste were generated in 2012, a figure projected to skyrocket to 2.2 billion tons by 2025 (Sharma and Jain, 2020).

13.8.3 Incineration with energy recovery

Incineration is a method in which waste materials are burned; hence, it is also known as thermal treatment. During this process, waste is transformed into ash, gas, and heat. Mostly, organic wastes with higher moisture content are present in developing nations. The presence of higher moisture content and, hence, incineration is not a suitable option for the management of agricultural waste. The presence of higher toxins and polycyclic aromatic hydrocarbons has become the leading cause of cancer. In addition to this, various infectious agents are released during incineration. This explains that burning toxic waste does not solve the problem because some of these byproducts are highly dangerous in comparison to their original materials. Incinerators release various pollutants in the atmosphere in the form of stack gases, ashes, and other wastes. Implementation of incineration requires higher capital and advanced technology. Therefore, it is not recommended as a standardized practice for waste disposal and management.

13.9 Conclusion

Integrated Waste Management Systems (IWMS) is an inclusive strategy for the management of different types of waste, including agricultural waste as well. It addresses various environmental issues and promotes sustainability and efficiency. Therefore, the integration of various waste management approaches, such as recycling, composting, biogas production, and waste-to-energy conversion, ensures that IWMS in the management of agricultural waste might be a very effective method of waste disposal and its conversion of value-added products. One of the major benefits of IWMS is it decreases the environmental impact of agricultural waste. Diversion of landfills and decrease in the emission of methane by composting and production of biogas, IWMS contributes to the reduction in the emission of greenhouse gases. In addition to this, the addition of nutrient-rich compost in the soil improves the fertility of the soil and reduces the requirement for chemical fertilizers, hence promoting the practices of sustainable farming. Moreover, IWMS supports the circular economy by turning waste into valuable resources. Production of biogas during the anaerobic digestion of agricultural waste can be used as a renewable energy source. Hence, it may provide a sustainable alternative to fossil fuels. It not only reduces energy costs for farmers but also decreases the reliance on nonrenewable energy sources. Implementation of IWMS also improves the nation's economy.

Farmers can also earn surplus income by selling the compost, biogas, and other byproducts of waste management processes. Moreover, the cost savings from decreased waste disposal fees and lower fertilizer and energy costs can significantly improve the net profitability of agricultural operations. Therefore, IWMS provides a holistic solution to the challenges of agricultural waste management. Therefore, the integration of different waste management practices promotes environmental sustainability and supports the circular economy, hence increasing economic viability for farmers. Hence, the implementation of IWMS in agriculture is a practical and forward-looking approach that aligns with the global objectives of sustainable development and mitigation of climate change.

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Chapter 14

Anaerobic digestion of waste for sustainable energy production: Principles, applications, and sustainable challenges

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Chapter Outline

14.1. Introduction 215
14.2. Types of waste from the industrial and agricultural sectors 217
14.3. Bioremediation 218
14.4. Valorization of waste through microbial decomposition 218
14.5. Biofuel production through waste digestion 220
14.6. Methane production coupled with waste biodegradation 221
14.7. Challenges and perspectives of waste energetic valorization 224
14.8. Conclusion 226
References **226**

14.1 Introduction

One of the most challenging problems that the world faces nowadays is managing the huge quantities of waste that are the result of the ever-evolving modern lifestyle of our societies worldwide. To have a clear idea on the dimension of the problem, it is approximated that the amount of municipal solid waste created is around 2.01 billion tons globally, with potential growth to 3.4 billion tons by 2050 (Kaza *et al.*, 2018). Therefore, working on solutions, especially those built on sustainable approaches, to mitigate the significant adverse effects of waste on the environment and the life within it is a paramount priority that the decision-makers should consider promptly and thoroughly.

One solution that is gaining much interest nowadays is bioremediation. Bioremediation is an eco-friendly and cost-effective process that uses living organisms, such as fungi, bacteria, algae, or plants, to remove or neutralize contaminants from polluted water, soil, or air. The organisms involved in this process metabolize the pollutants, degrading them into less hazardous compounds or accumulating them into their biomass. Bioremediation can be applied to eliminate a wide range of contaminants, including organic (pesticides, petroleum hydrocarbons, etc.) (Salah-Tazdaït and Tazdaït, 2024; Tazdaït and Salah-Tazdaït, 2021) and inorganic compounds (radionuclides and heavy metals) (Salah-Tazdaït and Tazdaït, 2022).

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The demand for renewable energy sources has grown significantly in recent years because of the environmental consequences and finite supply of fossil fuels. Utilizing anaerobic digestion of waste shows promise for generating renewable energy and is crucial in tackling these issues (Salah-Tazdaït and Tazdaït, 2019). Anaerobic digestion is a process in which organic materials, such as food waste and agricultural residues, are degraded by microorganisms in anaerobic conditions. This process generates biogas, which is mainly composed of carbon dioxide and methane. The latter can be captured, purified, and used as a renewable energy source for numerous applications, including vehicle fuel and electricity and heat production. Anaerobic digestion also lowers greenhouse gas emissions by rerouting organic waste from landfills and improves waste management practices by converting organic waste into fertilizers. Anaerobic digestion involves four key steps, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each carried out by specific groups of microorganisms with great biochemical, genetic, and physiological variety. The acetoclastic methanogenic archaea (*Methanosarcina* and *Methanothrix*) and hydrogenotrophic methanogenic archaea (*Methanogenium, Methanobrevibacter, Methanobacterium,* and *Methanococcus*) produce methane by anaerobically digesting organic wastes with heterotrophic microorganisms, which include hydrolytic and fermentative bacteria. The former carries out the hydrolysis process, and the latter carries out the acidogenesis and acetogenesis processes. Additionally, the microbial generation of hydrogen has garnered significant interest in recent years. Various microbial species with taxonomic, biochemical, and physiological differences can generate hydrogen as a metabolic byproduct. The microorganisms are categorized as (Ntaikou, 2020):

(1) Heterotrophic facultative anaerobic bacteria that possess cytochromes and degrade formic acid to generate hydrogen (such as *Klebsiella pneumoniae, Citrobacter freundii, Enterobacter aerogenes,* and *Escherichia coli*).
(2) Obligatory anaerobic heterotrophic bacterium *Desulfovibrio desulfuricans* with a cytochrome system.
(3) Obligatory anaerobic heterotrophic bacteria that do not possess a cytochrome system (such as *Clostridium beijerinckii, Clostridium welchii, Ruminococcus albus,* anaerobic methylotrophic bacteria, and archaea). For instance, the main general catabolic pathway leading to hydrogen production in clostridia is given below (Reactions 1 and 2):

$$C_6H_{12}O_6 \text{ (glucose)} + 2NAD^+ \rightarrow 2CH_3COCOOH \text{ (2 pyruvic acid)} + 2NADH, H^+ \quad (1)$$

$$2CH_3COCOOH + 2H_2O \rightarrow 2CH_3COOH \text{ (acetic acid)} + 2H_2 + 2CO_2 \quad (2)$$

(4) Green algae, photoautotrophic cyanobacteria (including those capable of nitrogen fixation), and other photosynthetic bacteria capable of generating H_2 either under aerobic or anaerobic conditions. Furthermore, under anaerobic conditions, photosynthetic bacteria, including the purple non-sulfur bacteria, are unable to generate H_2 directly from water; they need an external supply of organic carbon to sustain their growth. This bacterial group generates photoheterotrophically hydrogen by degrading organic compounds like pyruvate, lactate, and acetate (Gupta *et al.*, 2024). For example, the degradation of lactic acid is shown in Reaction 3:

$$CH_3CH(OH)COOH + H_2O + h\nu \text{ (Light)} \rightarrow 6H_2 + 3CO_2 \quad (3)$$

It was reported that various types of waste, such as sewage sludge, solid recovered fuel, and municipal solid waste, are suitable for biological hydrogen production (Lui *et al.*, 2020).

Microbial fuel cells (MFCs) offer an eco-friendly option for directly producing electricity from electron donors oxidized by microorganisms. MFCs make it possible to directly transform the chemical energy contained in organic compounds into electrical energy. The microorganisms in MFCs form a biofilm by colonizing a conductive surface and acting as catalysts for substrate oxidation, enabling the production of electrons. They can come from several ecosystems, such as anaerobic activated sludge, marine sediments, and rhizosphere. MFCs can be powered by a wide range of wasted organic compounds, such as sugarcane effluent (Sreelekshmy *et al.*, 2020), poultry droppings (Oyiwona *et al.*, 2018), potato waste (Du and Li, 2015), rice bran, leaf waste, cow dung, fruit waste, and food waste (Azizul Moqsud, 2021).

The anaerobic digestion process of waste is an intricate process whose efficiency and effectiveness are influenced by various factors, such as temperature, pH, composition of the waste, microbial composition and structure, carbon-to-nitrogen ratio, digestor configuration, retention time, moisture content (Mohd Sabri *et al.*, 2022), and the presence of inhibitory compounds such as heavy metals (Nguyen *et al.*, 2019) and hydrogen sulfide (Mutegoa and Sahini, 2023).

Therefore, it is crucial to comprehend and optimize these factors to maximize the efficiency and stability of anaerobic digestion processes, thereby improving metabolites production and waste management efficiency.

This chapter describes the current understanding of integrating environmentally friendly energy generation from different types of waste produced by human activities in the agro-industrial and agricultural sectors and methods for

reducing pollution. The chapter also highlights the difficulties and potential for enhancing efficiencies of energy production in waste anaerobic digestion processes.

14.2 Types of waste from the industrial and agricultural sectors

In most parts of the world, the agricultural and industrialization revolutions resulted in a significant increase in industrial and agricultural waste production. This everlasting growth poses challenges regarding public health, environmental protection, and waste management (Das *et al.*, 2019). With the expansion of agriculture and livestock farming, particularly in developing countries, the volume of agricultural waste is set to increase with concerns about manure, wastewater, and air pollutants. Furthermore, aquaculture generates waste primarily through feed, which requires appropriate waste management practices (Hooda *et al.*, 2000). On a global scale, these various wastes encompass a wide range of materials with potential value, and yet unfortunately, they are often considered non-productive products due to their economic inefficiency in collection, transport, and transformation. The waste generated by human activities can be mainly classified into industrial and agricultural categories.

Industrial waste includes liquid, solid, hazardous, and non-hazardous waste. Each waste type presents unique management and disposal challenges. This waste, originating from manufacturing or industrial processes, encompasses a variety of materials rendered useless during manufacturing operations.

Agricultural waste is the residue from the cultivation and processing of raw agricultural goods, ranging from fruits, vegetables, and crops to meat, poultry, and dairy products. Residues and byproducts generated within the agricultural sector constitute a substantial fraction of global agricultural output; they include animal (manure, animal carcasses), food processing, crops, and hazardous agricultural waste (pesticides). Although the amount of waste produced by the agricultural sector is significantly lower than that produced by other industries, its long-term pollution potential is high (Koul, Yakoob, and Shah, 2022).

As shown in Table 14.1, agricultural and industrial wastes can be classified according to various criteria, including nature, pollution characteristics, and industries of origin.

TABLE 14.1 Overall view of types of industrial and agricultural wastes.

Types of industrial waste	Description
Solid waste	Byproducts from manufacturing processes like iron and steel production or water treatment.
Liquid waste	Residuals in liquid from industries like chemical and pharmaceutical.
Biodegradable waste	Capable of decomposing naturally, often from food processing or textile mills.
Nonbiodegradable waste	Does not decompose easily; it includes plastics and radioactive materials.
Hazardous waste	Poses health and safety risks, often from factories or hospitals.
Non-hazardous waste	Materials not immediately harmful, like recycled waste from food or marble industries.
Types of agricultural waste	Description
Forest waste	• Encompasses various categories, such as branches, leaves, cones, etc.
Food waste	• Unused food products. • Can be composted or recycled.
Animal manure	• Waste from animals. • Valuable for improving soil health. • Excessive amounts can cause water pollution.
Agricultural plastic	• Plastic used in irrigation, packaging, etc. • Can persist for centuries, harming humans and wildlife.
Crop residues	• Leftover post-harvest plant materials, such as stems, leaves, roots, etc. • Rich in nutrients.
Pesticides and chemicals	• Useful for crop health but can endanger the environment. • Proper disposal prevents exposure to risks.

14.3 Bioremediation

14.3.1 Definition and principles of bioremediation

Bioremediation refers to the use of biological organisms to remediate an environmental problem, such as contaminated soil or contaminated water. In simpler terms, it is an approach for removing pollutants from the environment, subsequently restoring the original natural surroundings, and preventing further pollution (Hussein *et al.*, 2024). It is a set of techniques that can reduce a contaminant's toxicity, mobility, or volume in soil, subsoil, water, and gaseous effluents. Bioremediation technology uses microorganisms (bacteria, fungi, and/or microalgae) or plants (phytoremediation) to contain, eliminate, reduce, or transform contaminants in soils, sediments, water, and air (Saravanan *et al.*, 2023). Microorganisms can degrade complex contaminants through different metabolic pathways (Hussein *et al.*, 2024).

14.3.2 Mechanisms of bioremediation

A compound is "biodegradable" when it can undergo biological modifications to its structure, resulting in modifications to its physicochemical properties. Specific molecules are resistant to any degrading action over very long periods. The stability of these molecules depends on their chemical structure, concentration, and the characteristics of the surrounding environment.

Generally, the more a molecule is substituted, the more resistant it is to biodegradation. The substituent's position also plays a role. The replacement of carbon by other O, N, and S atoms, like multiple connections on the same carbon atom, changes the resistance to biotransformation of organic products (Dubey *et al.*, 2023; Saravanan *et al.*, 2023).

The presence of the substrate in too high concentrations can lead to the inhibition or inactivation of one or more enzymes involved in microbial metabolism (Yaashikaa and Kumar, 2022).

Microorganisms (bacteria, microalgae, and microscopic fungi) can reduce the organic pollution in polluted aqueous discharges. They are also able to bioaccumulate inorganic compounds, such as heavy metals. Indeed, metal ions can be quickly adsorbed on the cell walls of microorganisms using a physical adsorption process. This phenomenon is followed by chemisorption when the ions have reached the cytoplasm. Metal ions are elements necessary for the metabolism of microorganisms but can prove toxic above specific concentrations (Navina *et al.*, 2024; Z. Wang *et al.*, 2023).

The biodegradation of certain organic products, which requires the action of different species of microorganisms, stops when one or more constituent species of the system are missing. Under controlled conditions, genetically modified microorganisms can effectively remove or reduce various contaminants due to their greater degradative capability (Rendón-Castrillón *et al.*, 2023; Saravanan *et al.*, 2023).

The degradation mechanisms of pollutants by bacteria and fungi depend on the structure of the pollutants and environmental conditions, in particular, the oxygen concentration. The most commonly used process is activated sludge. This process is limited by the high cost of sludge treatment and its ineffectiveness with regard to concentrated effluents or those containing bio-resistant substances.

14.4 Valorization of waste through microbial decomposition

14.4.1 Hydrogen production through agricultural waste digestion

Many genera of microorganisms (*Escherichia, Acinetobacter, Syntrophomonas, Clostridium, Enterobacter,* etc.) are capable of producing biohydrogen as a byproduct of their metabolism. This ability to produce hydrogen is most often carried out by the production of intracellular enzymes capable of regulating the redox elements of the cell.

Two groups of processes are distinguished:

a) Photobioprocesses, which require a light supply and use organic molecules' photofermentation properties. The microorganisms involved are photosynthetic (microalgae, cyanobacteria, and non-sulfur photosynthetic purple bacteria (*Rhodobacter, Rhodopseudomonas* sp., etc.). In this case, bacteria use light and simple organic molecules for their own growth. In this case, it is a question of hijacking the cellular functioning of normally nitrogen-fixing enzymes, nitrogenases (Pachaiappan *et al.*, 2024). Indeed, in the case of nutritional conditions limiting nitrogen, nitrogenases will evacuate the surplus of cellular electrons and protons in the form of hydrogen. However, this reaction is not very specific for nitrogenase, and the latter requires a high energy demand from the cell, in the form of ATP, to function. The advantage here is that organic molecules can be used as long as the medium does not contain sources of ammonium ions, and the oxygen produced in the medium can overcome inhibition. Photofermentation can then serve as a complement to the production of hydrogen from byproducts' fermentation (Eroglu and Melis, 2011). However, photofermentation presents major obstacles linked to the use of light for its operation, in particular incident light, therefore

involving significant production areas. Nitrogenase is also less energetically efficient, which restricts bacterial growth. Finally, the main obstacle to using pure microorganisms is that the environment has to be carefully controlled, which restricts their use to industrial effluents with low protein content, most often in conjunction with a dark fermentation process (Keskin, Abo-Hashesh, and Hallenbeck, 2011; Sinha and Pandey, 2011).

b) Processes that do not require light, such as dark fermentation and microbial electrolysis cells. The way these processes are carried out depends on the type of substrate used, and it appears to be more suitable for the use of complex waste or effluents. The microorganisms involved are strict or facultative fermentative, anaerobic for dark fermentation, or electroactive bacteria for microbial electrolysis cells.

The main advantages of dark fermentation include the ability to convert a large number of carbon sources into biohydrogen while simultaneously generating molecules that may be of industrial interest at a lower cost (Eroglu and Melis, 2011; Sinha and Pandey, 2011). Pure culture has better conversion rates, but the conditions must be made sterile, either before the substrate is prepared or during the process, for example, by using hyperthermophilic microorganisms (>80°C). The constraints associated with the use of pure cultures also lie in the metabolic potential, which is limited to the physiological potential of the microorganisms used (Elsharnouby *et al.*, 2013). The main advantage of mixed cultures is that they can use all forms of substrates to produce hydrogen, including organic waste, by imposing specific growth conditions in bioprocesses. The main disadvantage of fermentation in mixed cultures is the numerous interactions that exist between microorganisms and the contaminations caused by the use of complex organic matter, which can lead to instabilities in the process over time. Thus, process management proves to be essential in this case, allowing for continuous operation over time (Cavinato *et al.*, 2012). Microbial electrolysis cells are a process for biologically converting organic matter into hydrogen by catalytic means, most often in a liquid medium. In the absence of oxygen, organic matter is converted into CO_2, and electrons are transferred to an electrical circuit by so-called electroactive bacteria. Because electroactive bacteria's metabolic potential is limited to a few molecules, hydrogen production processes are primarily carried out in mixed microbial cultures. By applying a potential difference of +0.2 V, a reduction of protons occurs at the cathode to produce hydrogen in a completely abiotic manner (without microorganisms). It has the advantage of being able to use a large number of different effluents to convert organic matter into hydrogen. The main disadvantage lies in the low current intensities generated by microorganisms, leading to large electrode sizes, and the instability of mixed microbial cultures, which can lead to microbial processes with reduced conversion performance. Another disadvantage is not being able to directly use solid substrates compared to dark fermentation processes (Ananthi *et al.*, 2024; Liu, Grot, and Logan, 2005).

14.1.1 Enzymes involved in the biological production of hydrogen (hydrogenases and nitrogenases)

The biological production of hydrogen requires two types of specific enzymes: hydrogenases and nitrogenases. Hydrogenases are the key enzymes of hydrogen metabolism because they regulate the cycle of redox elements in the microbial cell. Hydrogenases are enzymes that catalyze the reduction of protons generated during metabolic reactions and carried by reduced cellular elements into hydrogen. The hydrogenases then serve the cell to reoxidize these elements necessary for their growth (Ji *et al.*, 2023).

Hydrogenases are very widely distributed in life, and most are inhibited, sometimes irreversibly, by the presence of oxygen. Two categories of hydrogenases can be distinguished based on the nature of their active site:

- [FeFe]-Hydrogenases function in vivo preferentially to produce hydrogen. These are intracellular enzymes.
- [NiFe]-Hydrogenases can function in the direction of hydrogen production and consumption. Their active center has the particularity of having a strong affinity for hydrogen, although it is strongly inhibited by oxygen (Peters *et al.*, 2015).

The catalytic activity of [FeFe]-Hydrogenases is between 10 and 100 times higher than that of [NiFe]-Hydrogenases.

In some cases, less specific enzymes, such as nitrogenases, can also produce hydrogen. These enzymes are initially used by microorganisms to fix atmospheric nitrogen (N_2) to produce ammonium ions (NH_4^+), which can be directly assimilated by microbial cells. In the absence of a nitrogen source, nitrogenases reduce the cell's protons to hydrogen but with less efficiency. However, the energy yields are much lower than those of hydrogenases (Mishra, Kaushik, and Tiwari, 2018).

14.1.2 Photofermentation

In the absence of oxygen, non-sulfur photosynthetic purple bacteria of the genus *Rhodobacter* or *Rhodopseudomonas* produce hydrogen by photofermentation. In this case, light energy is used by these microorganisms to assimilate simple

sources of carbon, such as simple sugars (glucose) or organic molecules. Photofermentative microorganisms use organic molecules as electron donors to reduce cellular precursor elements for biomass synthesis (Moia *et al.*, 2024). This is particularly the case for intracellular ferredoxins. The reoxidation of ferredoxins occurs either via numerous metabolic synthesis pathways or by nitrogenase, a nitrogen-fixing enzyme (Levin, Pitt, and Love, 2004). This reaction occurs when the growth medium is deficient in nitrogen. It should be noted that nitrogenase is very energetically costly for the microbial cell, and the actual yields are low (Moia *et al.*, 2024).

Photofermentation with *Rhodobacter sphaeroides, Rhodospirillum rubrum, Rhodobacter capsulatus,* and *Rhodopseudomonas palustris* produced 55.81 mL/g biohydrogen using Alfa alfa biomass. However, *Rhodospirillum rubrum, Rhodobacter capsulatus,* and *Rhodopseudomonas palustris* produced 77.78 mL H_2/L per hour through photofermentation of potato residue (Putatunda et al., 2023).

14.1.3 Dark fermentation

Strict or facultative anaerobes produce hydrogen in the absence of oxygen by fermenting organic matter. In the case of strict anaerobes, the main production pathways are the fermentation pathways of sugars into acetate and butyrate.

In the case of dark fermentation processes, the main substrate concerns the use of organic sources either in the form of simple or complex sugars as part of the use of pure microorganisms, or in the same forms but also complex waste or effluents (Yang *et al.*, 2024).

Vegetables and fruits wastes were used to produce hydrogen with 60 and 200 L/kg of yield, respectively (Melikoglu and Tekin, 2024). In batch reactors, several types of agricultural waste were used to test biohydrogen production through dark fermentation. These included corn (7.6 ml H_2/h) and cotton stalks (0.29 ml H_2/h), rice straw (2.3 mmol H_2/g), wheat straw (5.416 mmol H_2/g), corn cob (112 ml/L), or co-digestion of sugarcane vinasse and bagasse (44.7%) (Ndayisenga *et al.*, 2024; Rashidi *et al.*, 2024; Sindhu *et al.*, 2024).

14.1.4 Microbial electrolysis cell (MEC)

It is a process where organic substrates are oxidized at the anode in the presence of a microbial biofilm, which plays the role of an electrocatalyst. Indeed, in the absence of oxygen, many microorganisms, called "electroactive," are capable of converting organic matter into CO_2 and into electrons and protons. Electrons and protons are transferred to another compartment (abiotic) to carry out the hydrogen synthesis reaction by applying a given voltage. Therefore, the microbial metabolism involved is not specific to hydrogen production; it is linked to the capacity to transfer electrons to a solid support (anode). The main microorganisms isolated and identified as electroactive belong to many different microbial groups (actinobacteria, firmicutes, acidobacteria, and proteobacteria [α, β, γ, δ]). These microorganisms are called ARB, or "anode respiring bacteria," because they have the ability to exchange electrons with an electrode. The majority of processes using complex effluents are operated in mixed cultures, where the microbial processes involved are still little known. This technique constitutes a solution perfectly suited to a situation where there are local needs for hydrogen with effluent treatment (Arun *et al.*, 2024; Noori *et al.*, 2024; Sharma *et al.*, 2024).

A microbial electrolysis cell was used to produce hydrogen using compost leachate, resulting in 55.1 mL of biohydrogen/g of chemical oxygen demand (Gautam *et al.*, 2023).

14.5 Biofuel production through waste digestion

First-generation biofuels come from the extraction of corn, rapeseed, sunflower oils, and also from sugarcane or beet. However, this generation of biofuels, which involve the occupation of large areas of land and compete with food production, has been heavily criticized and is gradually being abandoned. Second-generation biofuels are obtained by the conversion of non-edible biomass (wood, plants, and waste), mainly lignocellulosic biomass; this is, in fact, more interesting, available in large quantities, and inexpensive, and above all, it does not compete with food. Finally, third-generation biofuels are obtained by the conversion of algal biomass (micro- or macroalgae, or marine organisms).

Biofuels derived from anaerobic waste digestion are discussed in the following section:

14.5.1 Bioethanol production

Bioethanol is the most widely used liquid biofuel in the world. It is mainly produced by microbial fermentation of sugar or starch from various raw materials, including sugarcane, sugar beet, corn, cereals, agricultural waste, forest waste, municipal waste, livestock manure, etc. When the sugars are present in the form of polysaccharides, a hydrolysis process (acid or enzymatic) is generally used for delignification and the formation of fermentable sugars before fermentation. Glucose

($C_6H_{12}O_6$) and sucrose ($C_{12}H_{22}O_{11}$) can be converted into ethanol (C_2H_5OH) and CO_2 by fermentation under anaerobic conditions by the yeast *Saccharomyces cerevisiae*, according to the following reactions (Reactions 4 and 5):

$$C_6H_{12}O_6 + H_2O \rightarrow 2C_2H_5OH + 2CO_2 \quad (4)$$

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 4C_2H_5OH + 4CO_2 \quad (5)$$

Distillation and dehydration are then used to produce an alcohol without high octane, also called dehydrated ethanol or anhydrous ethanol. During the fermentation process, several physicochemical factors, such as temperature, dissolved oxygen, pH, and nutrients, must be controlled for the proper development of the microorganism. Once these parameters have been adjusted, fermentation starts and generally takes place in batches in order to avoid the excessive formation of gas and foam. Fermentation tanks are generally closed and have an internal or external temperature control system. After fermentation, the cells could be collected by centrifugation, treated with sulfuric acid and nutrients to improve viability, and used as an inoculum for subsequent fermentation (Jain and Kumar, 2024; Roy Choudhury, Das, and Chakraborty, 2024).

Agricultural waste can be used to produce 40.6 g of bioethanol/L of carrot pulp. Coconut husks were also used to produce bioethanol with a yield of 59.6% (Jayakumar *et al.*, 2023). Sugarcane was employed to produce bioethanol with a yield of 94% (Shenbagamuthuraman *et al.*, 2022).

14.5.2 Butanol production

Butanol is obtained by acetonobutyl fermentation. This anaerobic fermentation transforms many monomeric sugars into butanol, acetone, and ethanol. Some clostridia (*Clostridium acetobutylicum, Clostridium beijerinckii, Clostridium pasteurianum, Clostridium sporogenes, Clostridium saccharoperbutylacetonicum,* and *Clostridium saccharobutylicum*) naturally form butanol. A typical feature of clostridial production is the production of a two-phase solvent in fermentation. The first phase is the acidogenic phase, during which acids are formed. Acetate, butyrate, hydrogen, and carbon dioxide are obtained as the main products during this phase. This acidogenic phase generally takes place during the exponential growth stage. The second phase is when the solventogenic acids are re-assimilated and used in the production of acetone, butanol, and ethanol (or isopropanol, instead of acetone in certain strains of *Clostridium beijerinckii*). Solventogenesis is tightly coupled to sporulation (Patakova *et al.*, 2022; Pugazhendhi *et al.*, 2019).

Traditionally, butanol is produced in batch reactors, and the product is recovered by distillation. The batch mode fermentation system is initiated with a solution generally composed of molasses or corn starch. The medium containing the substrate and nutrients is sterilized in autoclaves at 121°C, followed by cooling under a nitrogen or carbon dioxide atmosphere (Sadh *et al.*, 2023).

After cooling, the reactor is inoculated with the culture, and the fermentation is started. During fermentation, butanol is accumulated. Low butanol productivity in batch reactors is due to its toxicity, as well as reactor maintenance, which includes loading, sterilization, and cleaning (Paredes *et al.*, 2022).

Several studies have used agricultural waste to produce butanol through fermentation. *Clostridium beijerinckii* was used for corn mash and corn straw fermentation. *Clostridium acetobutylicum* was used for rice bran, apple and pear peel, and orange peel waste fermentations (Sadh *et al.*, 2023).

14.6 Methane production coupled with waste biodegradation

Methanization allows the production of methane from organic matter (industrial effluents, organic household waste, or livestock droppings).

Methanization is carried out in four stages:

- **Hydrolysis** of the substrate into simple, soluble compounds.
- **Acidogenesis and acetogenesis** allow the formation of volatile acids, ammonia, carbon dioxide, hydrogen, and acetic acid (Khan *et al.*, 2023).
- **Methanogenesis**, which occurs either through acetic acid degradation (Reaction 6) or hydrogen oxidation (Reactions 7 or 8).

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (6)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (7)$$

$$CH_3COOH + 4H_2 \rightarrow 2CH_4 + 2H_2O \quad (8)$$

Agricultural (corn straw, cattle manure, etc.) and forestry wastes can be converted into methane (Liu *et al.*, 2024; Zou *et al.*, 2024).

An eligible resource for agricultural methanization is biomass, which can be converted into methane. This resource's eligibility depends on its bio-methanogenic potential and bio-physico-chemical properties. The presence of undesirable materials and the biochemical composition are sources of technical limitations in its conversion to methane. Indeed, not all organic resources have the same methane production potential. It depends on their structural properties (heterogeneity of particle size, water retention capacity) and biochemical composition (soluble sugars or non-soluble carbohydrate polymers, lipids, and proteins). Among these organic resources, there are easily biodegradable products, such as simple sugars, fats, and short-chain organic acids. But other compounds are less easily biodegradable (or more difficult to access), such as hemicelluloses, cellulose, and lignin. Among the eligible resources for anaerobic digestion, agricultural (corn straw, cattle manure, etc.) and forestry wastes can be converted into methane (Liu *et al.*, 2024; Romio, Vedel Wegener Kofoed, and Bjarne Møller, 2022; Zou *et al.*, 2024).

14.6.1 Role of nanoparticles (NPs) on methanogenesis performance

A very promising technique using NPs has recently gained interest, which involves the integration of biological processes with biogenic or non-biogenic organic or inorganic NPs to achieve highly effective and efficient bioprocesses, including bioremediation and primary and secondary metabolite production.

NPs have garnered significant interest across multiple domains, such as bioremediation (Chaudhary *et al.*, 2023) and pharmacology (Roy *et al.*, 2023), owing to their distinctive physical and chemical characteristics. Nevertheless, stringent restrictions and guidelines are essential to guarantee the secure and careful utilization of this technology.

NPs are produced by various chemical techniques such as hydrothermal, co-precipitation, co-reduction, and sol-gel, as well as biogenic processes that use microorganisms or plants (Chauhan *et al.*, 2023).

During anaerobic digestion of organic substances, methanogenesis is carried out by hydrogenotrophic (*Methanobacterium, Methanosprillum, Methanobrevibacter, Methanogenium,* etc.), acetoclastic (*Methanothrix, Methanosaeta,* and *Methanosarcina*), and methylotrophic (*Methanomethylovorans, Methanolobus,* etc.) methanogens. In the case of hydrogenotrophic methanogenesis, methane is produced by a reaction, in which H_2 serves as the source of electrons and CO_2 as the final receiver of these electrons (Reaction 9):

$$4H_2 + H_2CO_3 \rightarrow CH_4 + 3H_2O \ \Delta G^{\circ\prime} = -136 \text{ kJ/mol} \quad (9)$$

The H_2 and CO_2, which fuel this reaction, result from the oxidation of different organic acids, such as propionic acid according to the following reaction (Reaction 10):

$$CH_3CH_2COOH + 3H_2O \rightarrow CH_3COOH + H_2CO_3 + 3H_2 \ \Delta G^{\circ\prime} = +76 \text{ kJ/mol} \quad (10)$$

It should be noted that Reaction 10 is thermodynamically unfavorable (standard biochemical free energy variation ($\Delta G^{\circ\prime}$) > 0) at high H_2 pressure (higher than 1 Pa). This reaction becomes favorable (possible) only in the presence of hydrogenotrophic methanogens, which consume the excess H_2 through their hydrogenase activities. This is a syntrophic relationship between H_2-producing bacteria, such as *Syntrophobacter* and *Syntrophomonas,* and other H_2 consumers, known as mediated interspecies transfer involving H_2 [interspecies hydrogen transfer (IHT)]. The coupling between reactions 9 and 10 results in a global reaction of which $\Delta G^{\circ\prime}$ is negative (-60 kJ/mol). Nevertheless, during anaerobic degradation, the H_2 pressure is mainly high, which hampers the process. Thus, more efficient electron transfer pathways are needed to overcome the energy obstacle in the anaerobic digestion process (Wu *et al.*, 2023). Another mediated interspecies transfer pathway involving formate has been well documented. In this pathway, the formate produced during the anaerobic digestion process can either be converted into H_2 and CO_2 by the formate dehydrogenase activity of the syntrophic bacteria before being converted into CH_4 or directly converted into CH_4 by the formate hydrogenlyase complex of the hydrogenotrophic methanogens (Shen *et al.*, 2016). Recent research has reported that certain exoelectrogenic microorganisms in association with methanogens are capable of directly transferring electrons (direct interspecies transfer [DIET]) through three main mechanisms, using (1) electroconductive pili, (2) extracellular cytochromes, and (3) conductive materials, including nanoparticles, which act as efficient electron donors or carriers. These mechanisms are depicted in Figure 14.1.

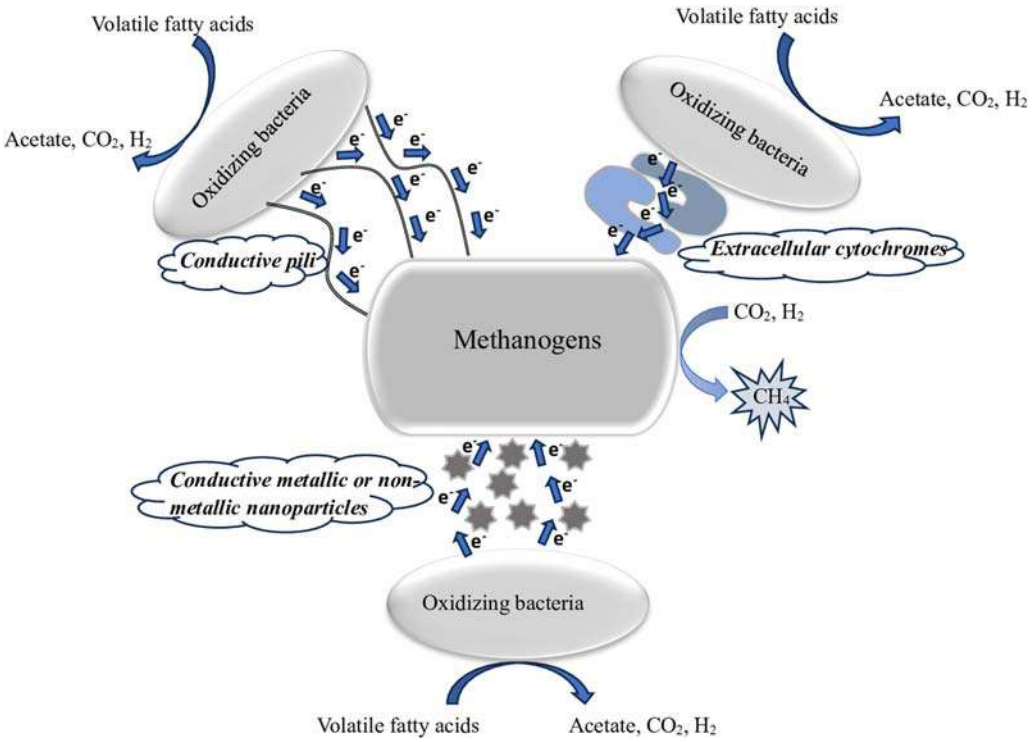


FIGURE 14.1 **Mechanisms of direct interspecies electron transfer during methanogenesis.** The provided figure depicts a diagram showcasing three mechanisms that facilitate the direct transmission of electrons between oxidizing and methanogenic bacteria in the process of methanogenesis. The mechanisms involve conductive pili, extracellular cytochromes, and conductive nanoparticles.

In acetoclastic methanogenesis, acetate is first activated to acetyl-CoA, and then its carbonyl and methyl groups are converted into CO_2 and CH_4, respectively. On the other hand, in methylotrophic methanogenesis, methyltransferase systems use mono-, di-, or trimethylamines or methanol to generate CH_4 (Kurth, Op den Camp, and Welte, 2020).

The following part of the chapter discusses recent research studies that have explored the use of NPs (nanomaterials) to improve the performance of microbial anaerobic digestion of different wastes.

Many research studies have evidenced that the use of NPs with anaerobic digestion of various wastes can result in better biogas production yields. The anaerobic degradation process can be enhanced using different NPs, such as metal oxides (silicon dioxide (SiO_2), titanium dioxide (TiO_2), zinc oxide (ZnO), and aluminum oxide (Al_2O_3) and zerovalent iron (ZVI) (Jadhav *et al.*, 2022). Thus, application of three different NPs, namely ZVI, ferric oxide (Fe_2O_3), and magnetite (Fe_3O_4) (with 50, 30, and 20 average diameters, respectively), to improve the methanogenesis performance of anaerobic granular sludge (AGS), characterized with about a 3 mm particle diameter and about 25 mL/g VSS (volatile suspended solids) sludge volume index (Li *et al.*, 2022). To further improve the process, the authors carried out another set of experiments in which the AGS was treated with two EPS (exopolysaccharides) disrupting agents (3 mM D-tyrosine and 3 mM norspermidine), which create pores, facilitating more NPs to be incorporated into the EPS. It was reported that all the tested NPs caused a significant enhancement in methane production compared to non-treated AGS, with increases ranging from 189.71 to 243.32%, 20.37 to 204.95%, and 36.49 to 85.17% for ZVI, Fe_2O_3, and Fe_3O_4, respectively. Also, adding D-tyrosine and norspermidine made methane production increase even more, but only for AGS that was loaded with Fe_2O_3 (184.58%) and Fe_3O_4 (48.68%). Furthermore, adding D-tyrosine and norspermidine caused a further increase in methane production, but only for AGS loaded with Fe_2O_3 (184.58%) and Fe_3O_4 (48.68%). The authors suggested that ZVI and iron oxides included in AGS could act as conductive substances, which have the ability to create a pathway for electrons to flow between syntrophic microorganisms during anaerobic digestion, thus facilitating DIET.

In another study, three different concentrations of ZVI NPs (0.01, 1, and 5 mg/g soil) were evaluated for their impact on hydrogenotrophic methanogenesis in flooded rice paddy soil samples in batch experiments for 29 days. It was evidenced that adding ZVI NPs effectively enhanced acetate degradation and methanogenesis in a concentration-related manner. When compared with the control experiment (without NPs addition), adding 5 mg/g soil of ZVI NPs had the greatest impact, with 82.4% increase in cumulative methane yield, followed by 1 mg/g soil (27%) and 0.01 mg/g soil (13.1%). The

positive effect of ZVI NPs on methane production was further proven by metagenomic analysis performed at the end of the experiments, which clearly showed that increasing the concentration of ZVI NPs resulted in increase in the relative abundance of methanogens, particularly the hydrogenotrophic methanogens, namely *Methanocella* and *Methanobacterium,* pertaining to the families *Methanocellaceae* and *Methanobacteriaceae,* respectively (Peng *et al.*, 2024).

Ma *et al.* (2020) performed batch experiments in which they observed the effect of TiO_2 (hydrophilic anatase) NPs on methane production in wetland sediment sampled from the Jiulong River Mangrove Nature Reserve (China). The TiO_2 NPs at 60 mg/g sediment with 100 nm particle size were tested in the presence of different short-chain organic acids (sodium propionate [13.3 mM], sodium acetate [30 mM], and sodium butyrate [10 mM]) serving as carbon sources. The results showed that methane production was significantly higher in the experiments with TiO_2 NPs incorporation than in the control group (without NPs), with maximum cumulative methane production enhancements of 6.8, 7.8, and 25.2% in the presence of butyrate, propionate, and acetate, respectively, indicating the positive effect of TiO_2 NPs on the DIET process within the sediment under investigation. Additionally, out of the three carbon sources used, propionate and acetate degradations were the most positively affected by TiO_2 NPs. On the other hand, the TiO_2 NPs supplement induced the enrichment of the *Euryarchaeota* phylum, which holds the methanogens of archaea.

Wang, Liu, and Yang (2023) studied the effects of two types of magnetite-loaded biochar NPs on the anaerobic digestion performance of propionate. The two types of NPs were synthesized from magnetite and two types of biochar, which were obtained from solid biogas residues and organic household waste. The experiments were performed in batch mode at 30°C and pH 7. Results indicated that NPs addition significantly enhanced methane production compared with the control. As observed, the lag time of methane production was remarkably shortened by about 68%, passing from about 22 days in the control experiment to about only 7 days with NPs supplement. Moreover, the system that used magnetite/biochar-based biogas residues exhibited better performance, producing 47% more methane than the system that used magnetite/biochar-based household waste. The nanocomposites used in this study act very likely as a conductive material, stimulating the DIET process between syntrophic bacteria and methanogens during the syntrophic methanogenesis process.

Table 14.2 gives some other examples of NPs used to improve the methanogenesis process during the digestion of different substrates including wastes.

14.7 Challenges and perspectives of waste energetic valorization

Multiple studies have emphasized the advantages of anaerobic digestion, such as the retrieval of energy from different wastes (agricultural, industrial, and municipal) and the safeguarding of the environment. Anaerobic digestion of organic waste is a sustainable and cost-effective method for producing renewable biofuel in the form of bioethanol, biomethane, biodiesel, or biohydrogen. Nevertheless, biofuels commonly struggle to match the commercial competitiveness of fossil fuels due to their higher production and processing costs. On the other hand, proper comprehension of the intricate steps of anaerobic digestion is essential for optimizing its effectiveness for waste management and energy generation.

Some perspectives of great interest have emerged, which include:

- Applying process intensification technologies, which refer to any progress made in a given process that leads to the development of significantly smaller, more energy-efficient, and safer systems, would help to increase the performance of biogas production during anaerobic digestion. Some of these technologies include membrane bioreactors, intensified bioreactor designs (integrating both reaction and separation processes within a single operation unit), optimizing mixing specific power (McLeod, Othman and Parthasarathy, 2019), electrolysis pretreatment and electro-fermentation (Shtepa *et al.*, 2023), and dry anaerobic digestion reactors (Sganzerla *et al.*, 2023).
- According to the waste used and the transformation method that leads to its production, the biogases are currently generated using first-generation (corn, starch, wheat, etc.) and second-generation (grass, bagasse, straw, etc.) feedstocks. An emerging technology exploiting high-yield photosynthetic bioreactors to culture eukaryotic and prokaryotic microalgae (cyanobacteria) would serve as a third-generation feedstock for biogas generation through anaerobic digestion (Sachin Powar *et al.*, 2022). On the other hand, the supplementation of cheap organic materials, such as molasses and manure, which serve as carbon sources, could improve microalgae growth. The oxidative degradation of these organic compounds by heterotrophic bacteria could release high levels of CO_2 necessary for microalgae growth.
- Genetically engineered crops are also a promising technology that could offer high-gas-yielding feedstock. Furthermore, a potential method for enhancing H_2 production in photosynthetic organisms involves conducting genetic screening to identify mutants with improved capacity for efficient H_2 generation using organic wastes.
- The economic viability of anaerobic digestion for waste management and energy production can take advantage of the process intensification approach by implementing innovative production processes and using low-cost alternative

TABLE 14.2 Examples of NPs and nanocomposites used to improve methanogenesis.

Source of methanogens	Waste (substrate)	Type of bioprocess/ duration of the experiment	NPs/nanocomposites	Methane production increased compared to the control	Reference
Anaerobic sludge	Municipal wastewater sludge	Batch experiments/25 days	Fe_3O_4	1.7-fold (120 mg/L NPs with 12−18 nm diameter, at 37 ± 1°C) 1.4-fold (250 mg/L NPs with 50−100 nm diameter, at 37 ± 1°C)	(Hassanpourmoghadam *et al.*, 2023)
Food waste anaerobic digestion system	Food waste	Batch experiments/65 days	ZVI Fe_2O_3 Particle size of Fe_3O_4 300-600 nm	2.7 ± 1.3% (ZVI at 2 g/L) 8.5 (ZVI at 5 g/L) 7.6 ± 0.3% (ZVI at 10 g/L) 5.4 ± 0.2% (Fe_2O_3 at 2 g/L) 4.4 ± 1.8% (Fe_2O_3 at 5 g/L) at 37 ± 1°C 6.7 ± 0.8% (Fe_2O_3 at 10 g/L) 5.9 ± 1% (Fe_3O_4 at 2 g/L) 6 ± 1.7% (Fe_3O_4 at 5 g/L) 3.2% (Fe_3O_4 at 10 g/L)	(P. Wang *et al.*, 2023)
Anaerobic sludge	Synthetic wastewater containing 4 g/L glucose, 400 mg/L NH_4Cl, 40 mg/L KH_2PO_4, and 78 mg/L $K_2HPO_4 \cdot 3H_2O$	Batch experiments/ 24 h	Fe_3O_4@polyaniline composites (a diameter of 1 μm) with different Fe_3O_4 loadings (20, 30, 40, and 50%)	26.03% (20% Fe_3O_4@polyaniline) 16.75% (30% Fe_3O_4@polyaniline) at 35 ± 1°C 26.98% (40% Fe_3O_4@polyaniline) 17.58% (50% Fe_3O_4@polyaniline)	(Huang *et al.*, 2022)
Anaerobic sludge	Corn straw	Batch experiments/26 days	ZVI (an average diameter of 50 nm) + CO_2-nanobubble water	26.16% (0.5 g/L + 250 mL CO_2-nanobubble water, at 35°C)	(He *et al.*, 2023)
Anaerobic sludge	Waste activated sludge	Batch experiments/35 days	$NiFe_2O_4$ (a pore diameter of 11.08 nm)	≈22% (0.25 g/L $NiFe_2O_4$, at 35 ± 1°C)	(Zhou *et al.*, 2022)
Anaerobic sludge	Sugar refinery wastewater	Batch experiments/21 days	$AlFe_2O_4$ (a particle size of 5.9 nm) and $MgFe_2O_4$ (particle size of 5.7 nm)	20% (3 mg/L $MgFe_2O_4$, at 35°C) 18.6% (3 mg/L $AlFe_2O_4$, at 35°C)	(Amo-Duodu *et al.*, 2023)
Cow manure	Whey	Batch experiments/45 days	Co_3O_4 (a particle size of 26 ± 2.1 nm) photoactivated by using a halogen lamp for 30 min	6-fold (Co_3O_4 at 5 g/L) 2.7-fold (Co_3O_4 at 2 mg/L) 37.5 ± 0.3°C 2.4-fold (Co_3O_4 at 1 mg/L)	(Samer *et al.*, 2022)
Anaerobic sludge	Glucose at 400 mg-COD[a]/L	Up-flow anaerobic sludge blanket/55 days	Nano-graphene (a diameter of 0.5-2 μm)	14.3% (Nano-graphene at 30 mg/L, at 10°C, 6 h HRT[b])	(Tian *et al.*, 2017)
Paddy soil slurry	Rice straw	Batch experiments/38 days	Fe_3O_4	16.6% (Fe_3O_4 at 8 mM at 30°C)	(Huang *et al.*, 2020)
Anaerobic cattle manure	Watered cattle manure	Batch experiments/30 days	Ni (a particle size of 65-114 nm)	70.46% (Ni at 2 mg/L, at 33 ± 0.5°C)	(Abdelwahab *et al.*, 2023)
Anaerobic sludge	Starch wastewater	Batch experiments/8 days	Granular activated carbon (GAC)-MnO_2 nanocomposites	36% (GAC-MnO_2 at 1.5 g/g VSS[c], at 30 ± 1°C)	(Yang *et al.*, 2020)

[a] *Chemical oxygen demand.*
[b] *Hydraulic retention time.*
[c] *Volatile suspended solids.*

feedstocks capable of reducing the total biogas processing cost and improving sustainability, paving the path to a circular economy transition.

- Lastly, using NPs technology has proven to be effective in methane production, as it not only shortens the lag time of the process but also remarkably enhances the methane production rate. To further improve the methanogenesis process, using sustainable biogenic NPs generated by eco-friendly processes with no inhibitory effects would be a good alternative to conventional chemically based methods for producing NPs. Therefore, there is significant potential for intensifying investigation in this developing area.

14.8 Conclusion

Anaerobic digestion is a biological-based process that provides a sustainable and eco-friendly method for energy generation and waste management. Anaerobic digestion, in fact, is an essential process in the production of renewable energy. It involves transforming organic waste into biogas, which helps to decrease the release of greenhouse gases. Furthermore, it contributes to better waste management practices and supports the development of sustainable agriculture.

Although extensive research efforts have been conducted on the cost-effectiveness of anaerobic digestion for waste management and methane generation, some major disadvantages persist, chiefly the instability of the process due to the complex structure and interaction between the different categories of microorganisms involved in the process, whose activities are profoundly influenced by abiotic parameters such as pH, temperature, the chemical composition of treated wastes, and susceptibility to inhibitory factors such as high volatile fatty acids, sulfate, and ammonia concentrations. Furthermore, numerous studies have highlighted the benefits of using NPs as conductive materials aimed at improving methanogenesis, thanks to their physicochemical properties, which enhance electron transfer between exoelectrogenic bacteria and their partners, endoelectrogenic methanogens. This approach not only helps in reducing the lag time of the methanogenesis process but also remarkably improves methane generation yields. However, it has been shown that the metallic NPs (Fe_3O_4) exerted an inhibitory effect on propionate methanogenesis during wastewater treatment by decreasing the abundance of the hydrogenotrophic methanogen *Mathanobacterium* and the genes of quorum sensing involved in microbial interspecies interaction. Currently, research efforts are still ongoing to design more efficient NPs with cost-effective production, and further investigation is required to explore the actual application of NPs in wastewater treatment.

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Chapter 15

Waste-to-energy technologies: Harnessing biogas from agricultural waste

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Chapter Outline

15.1. Introduction 231
15.2. Biochemical conversion 232
15.3. Anaerobic digestion biogas production process 233
15.4. Pretreatment of agricultural waste biomass for biogas production 234
15.5. Operational methods and reactor designs 238
15.6. Factors affecting biogas production 239
15.7. Additives to enhance biogas production from agricultural wastes 241
15.8. Biogas upgrading 241
15.9. Biogas applications 244
15.10. Global overview of biogas production 245
15.11. Biogas benefits and limitations 246
15.12. Future perspectives 248
15.13. Conclusion 249
References 249

15.1 Introduction

Using waste to generate energy is considered one of the best options for meeting the world's growing demand for energy. In general, there are two common types of waste-to-gas technologies depending on how the waste is processed: thermochemical and biochemical (Khalil *et al.*, 2019). Agricultural waste biomass is converted to gaseous fuels with higher calorific value by thermochemical methods such as gasification, pyrolysis, and direct combustion, for various uses (Ufitikirezi *et al.*, 2024). However, thermochemical technologies face the challenge of requiring elevated temperature and pressure conditions, which increases operating costs, and the need for further research to improve their cost-effectiveness (Ufitikirezi *et al.*, 2024). For biogas production, biochemical conversion is preferred because of its easy production process and direct use in various applications, such as fuels, internal combustion generators for electricity, microturbines, and fuel cells (Khalil *et al.*, 2019). In

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addition, biogas production generates digestate that can be used as a fertilizer or go through waste-to-energy thermal processes to produce other biofuels and biochar. In this way, a circular economy based on agriculture can be achieved, addressing the problems of recycling waste, energy production, and nutrient recovery (Kapoor *et al.*, 2020).

The combustion, gasification, and pyrolysis of biomass represent the three primary thermochemical processes for converting agricultural residues into gaseous fuels (Kapoor *et al.*, 2020). The most common method of biomass conversion is direct combustion, involving three stages: drying, reduction of the volume, and gas combustion (Ufitikirezi *et al.*, 2024). Suitable agricultural wastes for the combustion process include wood chips, sawdust, pellets, or bio-oil (Jameel *et al.*, 2024). During combustion, the agricultural waste biomass is burned with excess air, causing the volatile components of the lignocellulosic biomass, such as carbon, oxygen, hydrogen, nitrogen, and sulfur, to react with atmospheric oxygen to produce heat. As a result, the chemical energy of the biomass is converted into mechanical power or electricity (Kapoor *et al.*, 2020). The conversion efficiency of this technology ranges from 20 to 40%. The key factors influencing biomass combustion are the particle size, feedstock characteristics, temperature, and combustion environment (Kapoor *et al.*, 2020). However, from an environmental point of view, this process presents challenges owing to the substantial emissions of CO, CO_2, NOx, particulate matter, other pollutants, and ash management (Ufitikirezi *et al.*, 2024). However, combustion is a reliable, well-known, and widely used commercial technology for biomass conversion into thermal energy, comprising approximately 90% of the total biomass-derived energy (Kapoor *et al.*, 2020; Ufitikirezi *et al.*, 2024).

Co-combustion involves the simultaneous burning of multiple fuels to generate energy. When biomass is burned together with other fuels, it partially replaces fossil fuels, resulting in a net reduction in CO_2 emission. For instance, co-combusting biomass and coal have recently gained prominence (Ufitikirezi *et al.*, 2024). This process can be accomplished either by directly burning coal and biomass together or indirectly by first gasifying biomass to produce clean fuel gas, which is then combusted with coal in boilers. Compared with other thermochemical methods, it is an ideal technique for improving biomass-to-energy efficiency and significantly reducing greenhouse gas (GHG) emissions. However, using high proportions of biomass presents technical challenges, such as ensuring continuous biomass availability and addressing potential issues like slag formation, fouling, and corrosion (Atchike *et al.*, 2022; Ufitikirezi *et al.*, 2024).

Gasification is a thermochemical conversion method that is efficient and environmentally friendly (Francisco López *et al.*, 2024). This process converts biomass into a mixture of flammable gases (such as CO, CO_2, C_2H_4, CH_4, and H_2) and other impurities (such as nitrogen, sulfur, and alkaline compounds) at high temperatures (between 800 and 1100°C) under controlled oxidation conditions using partial oxygen for complete combustion (approximately 35% of O_2) or other oxidants gases such as steam and CO_2 (Kapoor *et al.*, 2020; Ufitikirezi *et al.*, 2024). Gasification using air typically results in a product with a low to moderate calorific value (from 4 to 7 MJ/Nm^3), while gasification with steam or oxygen produces a product with two times more calorific value (from 10 to 14 MJ/Nm^3) (Ufitikirezi *et al.*, 2024). Gasification produces synthesis gas or a mixed gas comprising around 1−2% CO_2, 15−25% CO, and 40−70% H_2 (Kapoor *et al.*, 2020). In general, gasification aims to produce valuable gases for further use or direct consumption, whereas combustion focuses on heat generation. Gasification is considered an environmentally friendly method because it uses solid byproducts in various forms and emits lower amounts of harmful gases. Its benefits include reduced CO_2 emissions, the need for smaller and lighter equipment, precise combustion control, and excellent thermal efficiency. However, it has disadvantages that limit its adaptability and efficiency, such as the need for a constant and adequate biomass supply (Ufitikirezi *et al.*, 2024).

Pyrolysis is a process where biomass is converted into biochar, bio-oil, and non-condensable gases (such as CH_4, CO_2, CO, H_2, and N_2) under atmospheric pressure without the presence of oxygen (Kapoor *et al.*, 2020). At high temperatures (above 800°C), pyrolysis maximizes gas production, between 450 and 800°C, bio-oil is mainly produced, whereas at low temperatures (below 450°C) the main product is biochar (Jameel *et al.*, 2024; Ufitikirezi *et al.*, 2024). The specific pyrolysis conditions and the chemical composition of the feedstock significantly influence the quantity and efficiency of the obtained products. Among these affecting factors are the pressure and temperature of the reaction, the volume and amount of agricultural waste feedstock, the residence time of the gas in the reactor, and the heating rate (Jameel *et al.*, 2024; Kapoor *et al.*, 2020).

In addition, thermochemical processes such as gasification and pyrolysis, using agricultural residues like rice husks, straw, corn cobs, sunflower bagasse, and sugarcane bagasse, can also be applied to generate hydrogen. In summary, during gasification, lignocellulosic biomass is converted into a mixture of gases such as hydrogen and carbon monoxide, among others, while pyrolysis produces bio-oil that can be refined into hydrocarbon liquid fuels and hydrogen-rich gas as a potential substitute for fossil fuels (Zielińska and Bułkowska, 2024).

15.2 Biochemical conversion

Anaerobic digestion is one of the main biochemical conversion processes used to transform agricultural wastes into gaseous energy products such as biogas and biohydrogen.

15.2.1 Anaerobic digestion

Anaerobic digestion is a biological process where organic materials such as food, animal, or agricultural wastes are broken down to produce biogas in the absence of oxygen, driven by microbial activity. This process comprises four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The biogas generated mainly contains methane (CH_4) (40-65% v/v) and carbon dioxide (CO_2) (35-55% v/v), with small amounts of hydrogen sulfide (0.1-3% v/v), moisture, and trace impurities. Digestate, a byproduct of this process, is a highly nutritious fertilizer, able to return to agriculture fields (Kapoor *et al.*, 2020). One of the main bottlenecks of using agricultural waste as a substrate for anaerobic digestion is the need for a pretreatment, which adds complexity to the process (Kapoor *et al.*, 2020).

On the other hand, in the field of biogas and biomethane, biohydrogen production is an emerging alternative (Calero *et al.*, 2023; Ginda and Szyba, 2023). Technically, hydrogen can be obtained through biogas steam reforming (BSR) and methane steam reforming (SMR), which differ in the presence of CO_2 in the feedstock (Calero *et al.*, 2023). BSR biogas allows pollutant-free biohydrogen to be obtained; however, depending on the technology used, its production by steam reforming can leave a significant carbon footprint (Ginda and Szyba, 2023). However, biohydrogen combustion in cells does not generate CO_2 or other greenhouse gases such as CH_4 and NH_3 (Ginda and Szyba, 2023).

15.3 Anaerobic digestion biogas production process

The increasing urbanization and rapid growth of the global population have driven up energy demands and the use of fossil fuels, contributing to global pollution issues (Bhatt and Tao, 2020). Therefore, finding environmentally friendly energy sources to replace fossil fuels has become imperative (Ullah Khan *et al.*, 2017). A viable waste-to-energy (WtE) alternative that has been widely implemented is the generation of biogas from waste with a high organic matter content (Bhatt and Tao, 2020).

Biogas, obtained from diverse feedstocks, is considered a renewable energy source (Chitara, Chauhan, and Singh, 2021; Kukwa *et al.*, 2022). It consists mostly of CH_4 (50-75%), CO_2 (25-50%), hydrogen sulfides, hydrogen, ammonia, and small proportions of nitrogen and oxygen (Atelge *et al.*, 2020). CH_4 has a wide variety of applications, can replace fossil fuels in electricity and heat production, and can be used as an energy source in vehicles (Chitara, Chauhan, and Singh, 2021).

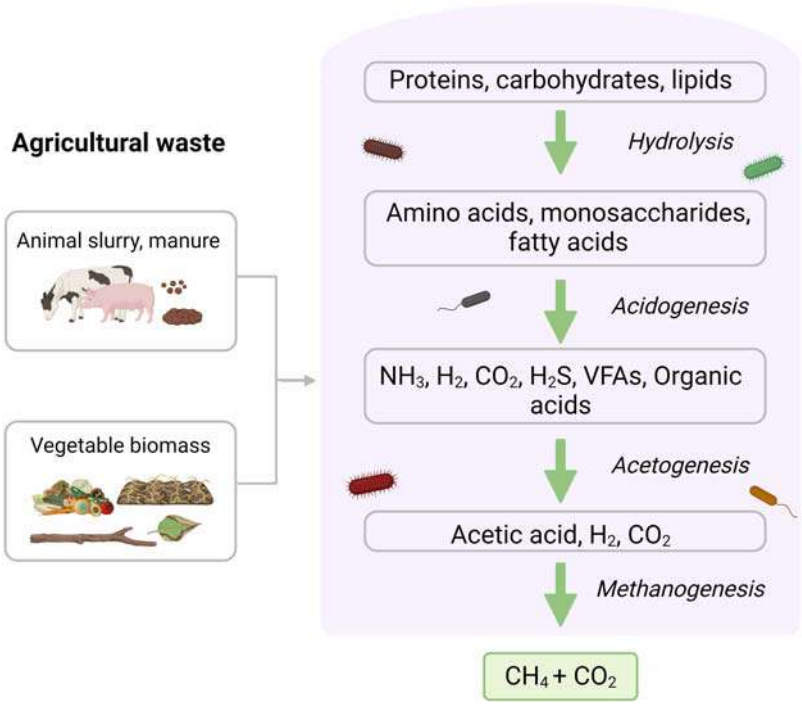
Biogas production is based on the degradation of complex molecules into simple molecules by microorganisms (Kabeyi, Olanrewaju, and Messineo, 2022). Anaerobic digestion (AD) is a four-stage biochemical process where microorganisms, under oxygen absence, degrade complex organic matter into smaller molecules, including gaseous elements (Mignogna *et al.*, 2023; Obaideen *et al.*, 2022). In the AD process, various wastes are used as an energy source by the microorganism to convert them into biogas, such as sludge, food, industrial, and agricultural waste, among others (Mignogna *et al.*, 2023). In this context, agricultural residues are accessible substrates that are commonly used as primary sources for biogas generation. These substrates include animal slurry, manure, agricultural byproducts, and crop residues, such as straw, stalks, and bark. These plant-derived residues consist mainly of lignin, cellulose, and hemicellulose, which make them difficult to digest (Atelge *et al.*, 2020). The produced biogas can be purified to be used as fuel, burned to generate electricity or heat, or incorporated into the national gas grid if it meets the required purity standards after treatment (Zupančič *et al.*, 2022). The remaining material, known as digested, consists of a wet mixture of nondegradable substances, microbial residues, microorganisms, and other components such as ammoniacal nitrogen, potassium oxide, and diphosphorus pentoxide, although the composition may vary depending on its origin. Furthermore, the digestate can be employed as a biofertilizer to increase crop yield in a sustainable manner (Ghosh *et al.*, 2020).

Biogas production involves the conversion of different residues into biogas in the absence of oxygen. It is carried out in four main stages (Figure 15.1): (1) hydrolysis, (2) acidogenesis, (3) acetogenesis, and (4) methanogenesis (Chitara, Chauhan, and Singh, 2021).

15.3.1 Hydrolysis

Hydrolysis represents the first stage of digestion, where biomolecules, such as proteins, polysaccharides, and lipids, are broken down into amino acids, monosaccharides, and fatty acids in the presence of proteases, amylases, lipases, and cellulases (Chitara, Chauhan, and Singh, 2021). The hydrolysis of lignocellulosic biomass represents a crucial rate-limiting step in the process, as lignocellulose is resistant to enzymatic attack and mechanical stress (Paudel *et al.*, 2017). Generally, this stage is the slowest stage of the process because of the presence of toxic byproducts and volatile fatty acids (VFAs). Therefore, the rate of hydrolysis can be increased through pretreatment of the substrate (Zupančič *et al.*, 2022) to remove the chemical and physical barriers and enhance its biodegradability (Paudel *et al.*, 2017).

FIGURE 15.1 Stages of anaerobic digestion.
Adapted from Gadirli et al., 2024.



15.3.2 Acidogenesis

The second stage is acidogenesis or also called fermentation, in which the monomers obtained in the previous stage are decomposed into organic acids such as acetic, propionic, and butyric acids, short-chain volatile fatty acids, ammonia, CO_2, hydrogen sulfide, and hydrogen (Kabeyi, Olanrewaju, and Messineo, 2022; Zupančič *et al.*, 2022). This stage occurs because of the activity of fermentative bacteria, which creates an acidic environment (Kabeyi, Olanrewaju, and Messineo, 2022).

15.3.3 Acetogenesis

The third stage is acetogenesis, in which acetic acid, hydrogen, and CO_2 are produced from the organic acids of the previous stage by the action of acetogenic bacteria (Chitara, Chauhan, and Singh, 2021; Zupančič *et al.*, 2022).

15.3.4 Methanogenesis

The last stage of the anaerobic digestion process is methanogenesis, where the products generated during the previous stage are converted into CH_4 and CO_2 (Chitara, Chauhan, and Singh, 2021). Two groups of methanogenic bacteria are involved in this stage: one uses CO_2 and hydrogen to produce CH_4, whereas the other group decomposes acetic acid into carbon dioxide and methane (Zupančič *et al.*, 2022).

15.4 Pretreatment of agricultural waste biomass for biogas production

The biogas production process starts with the pretreatment of the feedstock before it is introduced into the digester for anaerobic degradation (Kabeyi, Olanrewaju, and Messineo, 2022). In general, typical agricultural residues contain 15-20% lignin, 20-35% hemicellulose, and 35-50% cellulose. To facilitate the degradation of lignocellulosic biomasses, its complex structure, and recalcitrant properties, mechanical, physicochemical, thermochemical, and biological pretreatment methods are used (Awogbemi and Kallon, 2022).

This pretreatment step simplifies microbial digestion by allowing the organic matter in the substrate to be easily accessible by the microorganisms (Kasinath *et al.*, 2021). Pretreatment usually begins with feedstock washing, maceration, sieving, and pressing, depending on the condition and type of feedstock and pretreatment method (Kabeyi, Olanrewaju, and Messineo, 2022). For example, poultry, pig, and cow manure is generally viable for biogas plants, while lignocellulosic biomass

comprising different proportions of hemicellulose, cellulose, and lignin is more resistant to oxidation and microbial degradation.

Pretreatment strategies can be divided into physical (mechanical, ultrasonic, thermal, and microwave), chemical (alkaline, acidic, oxidative, and using organic solvents), biological (fungal, microbial consortium, enzymatic, and termites), and physicochemical (steam explosion, ammonia fiber extrusion, and explosion, alkali-heat pretreatment) (Awogbemi and Kallon, 2022). These strategies (Figure 15.2) increase the availability of feedstock for microbes by increasing the porosity, surface area, solubilization, and decrystallization of biomass.

15.4.1 Physical pretreatment

Physical pretreatment techniques are used to reduce particle size and improve the surface area of agricultural residues, ensuring the accessibility of enzymes and microbes during processing, reducing cellulose crystallinity, increasing conversion efficiency, and improving product yield. These techniques include mechanical, ultrasonic, thermal, and microwave pretreatments (Awogbemi and Kallon, 2022).

15.4.1.1 Mechanical pretreatment

Mechanical pretreatment applies mechanical force to reduce particle size, break down the structure of lignocellulose, and reduce the lignin content and degree of polymerization, facilitating the access of enzymes or chemicals to hemicellulose and cellulose. This process is carried out by cutting, milling, chipping, stirring, and shearing (Awogbemi and Kallon, 2022).

15.4.1.2 Ultrasonic pretreatment

Ultrasonic pretreatment uses high-energy vibrations to break down lignocellulose crystals, removing 80-100% of the lignin content in some residues (Awogbemi and Kallon, 2022). It is a new technology for lignocellulosic biomass (Naik, Poonia, and Chaudhari, 2021). Ultrasonic vibrations (frequency range 20 KHz to 500 MHz) generate cavitation bubbles, which, when broken, create high pressure and temperature, breaking the biomass structure and facilitating subsequent hydrolysis (Awogbemi and Kallon, 2022). By reducing the polymerization and crystallinity of cellulose, the production of furfural and hydroxymethyl furfural (HMF) is also minimized, both of which can inhibit microbial activity during anaerobic digestion (Joshi and Gogate, 2019). Despite ultrasonication being recognized as safe and efficient, most studies highlight concerns over its negative energy efficiency, casting doubt on its cost-effectiveness for biogas production (Li *et al.*, 2022).

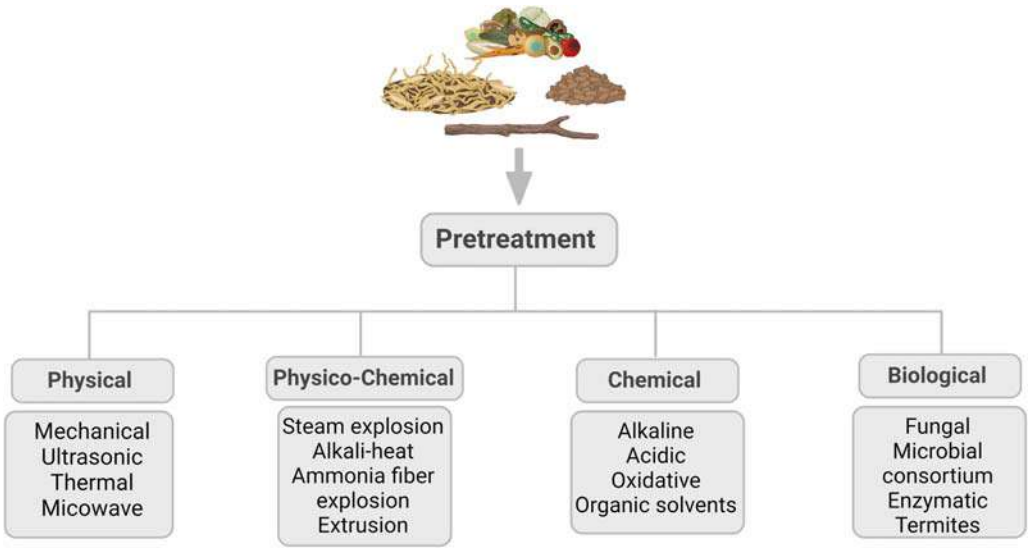


FIGURE 15.2 **Classification of agricultural waste pretreatments for biogas production.**

15.4.1.3 Thermal pretreatment

Thermal pretreatment consists of exposing the biomass to temperature variations over some time (Aworanti *et al.*, 2023). It includes methods such as steam explosion, use of liquid hot water, and hydrothermal pretreatment. For instance, hydrothermal pretreatment at 200°C for 90 minutes can increase the conversion of hemicellulose up to 96.4% (Aworanti *et al.*, 2023). Steam explosion is used as pretreatment for lignocellulosic biomass in a temperature range between 160 and 250°C and a pressure range between 5 and 50 bar (Aworanti *et al.*, 2023). Due to the intensity of mechanical and chemical change in this process, the biomass structure is broken down, allowing the release of cellulose and hemicellulose. Although this is ideal for hardwood, the release of inhibitory compounds is present when high temperatures in combination with ammonia or weak acids (Naik, Poonia, and Chaudhari, 2021). On the other hand, liquid hot-water pretreatment uses temperatures of 100-140°C and pressure of 1-2 bar to improve enzymatic digestibility. It is less severe than a steam explosion, reduces inhibitor formation, improves enzymatic digestibility of lignocellulosic biomass by removing hemicellulose and lignin, and makes cellulose more accessible for enzymatic hydrolysis (Naik, Poonia, and Chaudhari, 2021).

15.4.1.4 Microwave pretreatment

Microwave pretreatment uses electromagnetic radiation to penetrate the tissue of agricultural residues, weakening the forces that hold the components together (Awogbemi and Kallon, 2022). This method is popular because of its simple operation, low energy consumption, rapid heating, and lower inhibitor generation. It is usually used in combination with chemical reagents such as salts and acids to improve the results. Common parameters include a power of 100-1100 W and frequencies from 1 kHz to 300 GHz (Naik, Poonia, and Chaudhari, 2021).

15.4.2 Chemical pretreatment

Chemical pretreatments involve the use of specific compounds to break down the rigid structure of lignocellulose and improve the biodegradability of agricultural residues (Awogbemi and Kallon, 2022). This method includes the application of acids, alkalis, and oxidative and organic solvents (Awogbemi and Kallon, 2022; Aworanti *et al.*, 2023).

15.4.2.1 Acid pretreatment

Acids such as hydrochloric, sulfuric, nitric, and phosphoric are used to degrade the glycosidic bonds of lignocellulose and to break down hemicellulose and cellulose, promoting the release of fermentable sugars (Awogbemi and Kallon, 2022). It is recommended to use dilute versions of these acids, less than 4% by weight, as strong acids can generate excessive degradation of the feedstock, resulting in the loss of fermentable sugars and the formation of undesired byproducts that affect the performance of anaerobic digestion (Aworanti *et al.*, 2023). Generally, acid pretreatment is performed using dilute sulfuric (H_2SO_4) and hydrochloric acids (HCl) (Naik, Poonia, and Chaudhari, 2021). Research has shown that pretreatment with diluted phosphoric acid (H_3PO_4) and H_2SO_4 in eucalyptus chips and rice husks can achieve a sugar recovery efficiency up to 60% (Awogbemi and Kallon, 2022).

15.4.2.2 Alkaline pretreatment

This method uses alkaline reagents such as potassium hydroxide (KOH), calcium hydroxide ($CaOH_2$), sodium hydroxide (NaOH), and ammonium hydroxide (NH_4OH) to liquefy lignin and a portion of hemicellulose, reducing cellulose crystallinity and promoting biomass conversion. Although this pretreatment reduces environmental pollution and is cost-effective. However, it requires a prolonged reaction time and neutralization of the pretreated sludge (Awogbemi and Kallon, 2022). Alkaline pretreatment has been shown to significantly improve biogas and biomethane production compared to acid pretreatment as it prevents the decrease of pH in the culture media, providing a favorable condition for anaerobic digestion (Aworanti *et al.*, 2023).

15.4.2.3 Oxidative pretreatment

This pretreatment involves electrophilic substitution and the use of oxidizing agents like peracetic acid and hydrogen peroxide (Paudel *et al.*, 2017). The effectiveness of hydrogen peroxide pretreatment is favored under high pH conditions ($\sim$11.5) (Aworanti *et al.*, 2023; Paudel *et al.*, 2017). Under these conditions superoxide (O-) and hydroxyl (HO-) radicals are highly reactive, facilitating delignification and the production of monomeric sugars (Khan *et al.*, 2021; Paudel *et al.*, 2017). Ozone oxidizes lignocellulosic biomass, mainly degrading lignin, followed by hemicelluloses, and hardly affects cellulose. This improved the reactivity of the biomass for enzymatic hydrolysis. In ozonolysis, ozone is added to carbon double bonds to form compounds that decompose in the presence of water. Ozone also reacts with aromatic compounds,

opening rings, and byproducts with carbonyl and carboxylic groups (Santos *et al.*, 2018). In this regard, ozone and hydrogen peroxide are effective in improving biogas production and reducing lignin content in agricultural residues (Awogbemi and Kallon, 2022).

15.4.2.4 Pretreatment with organic solvents

This method applies solvents such as acetone, ethanol, methanol, and tetrahydrofuran to break the internal bonds of lignin and hemicelluloses, ensuring effective cellulose conversion. Often, acids or bases are used as catalysts to accelerate the reaction (Naik, Poonia, and Chaudhari, 2021). Acetone treatment, for instance, has been shown to remove up to 76% of the lignin from wheat straw (Awogbemi and Kallon, 2022).

15.4.3 Biological pretreatment

Biological pretreatment involves the use of microorganisms such as fungi and bacteria to degrade lignin, facilitating the conversion of lignocellulosic feedstocks into smaller molecules (Awogbemi and Kallon, 2022). This method is environmentally friendly, does not produce toxic inhibitors, and consumes little energy. However, its process is slow and may present microbial instability, resulting in unpredictable reactions (Awogbemi and Kallon, 2022; Aworanti *et al.*, 2023).

15.4.3.1 Fungal pretreatment

Fungal pretreatment is distinguished as a method that requires reduced chemical demands and low energy consumption, minimizing the generation of unwanted byproducts. Various brown rot fungi, soft rot fungi, and white rot fungi are used (Singh *et al.*, 2023). Brown rot fungi are normally used to degrade cellulose, while white and soft rot fungi are used for lignin and cellulose degradation (Aworanti *et al.*, 2023). In one study, the white-rot fungus *Peniophora incarnata* was used to pretreat wood waste, resulting in a 48% reduction in hemicellulose and a 70% reduction in lignin (Ma *et al.*, 2021).

15.4.3.2 Microbial consortium pretreatment

Microbial consortium pretreatment uses a mixture of microbial strains from various sources such as soil, wastewater, and animal excrement to break down both cellulose and hemicellulose in agricultural residues (Awogbemi and Kallon, 2022). The potential of a lignocellulolytic microbial consortium (LMC) to enhance biogas production in the anaerobic digestion of fiber-rich swine manure under thermophilic and mesophilic conditions has been reported. The greatest improvement in biogas and CH_4 production was observed at 37°C with a LMC/swine manure ratio of 1.5:1 mg VSS/g VS, which resulted in yields of 355 ml/g VS for biogas and 180 ml/g VS for CH_4, demonstrating an increase of 40% and 55%, respectively, increasing the efficiency of hemicellulose and cellulose degradation, maintaining the stability of the process for 90 days (Tuesorn *et al.*, 2013). In another study, microbes from landfills, decomposing straws, and wastewater were used to pretreat cassava waste, achieving a biogas efficiency of 96% (Zhang *et al.*, 2011).

15.4.3.3 Enzymatic pretreatment

Enzymatic pretreatment involves the application of hydrolytic and oxidative enzymes produced by fungi and bacteria; some examples include α-amylases, β-glucosidases, cellulases, cellobiases, endoglucanases, laccases, xylanases, proteases, pectinases, and peroxidases. Factors such as pH, substrate or raw material composition, temperature, incubation time, and reactor configuration influence the efficiency and activities of the enzymatic reaction (Aworanti *et al.*, 2023). This method has shown efficiency due to its short reaction times and low nutritional requirements, although its implementation is restricted by high cost and selectivity (Aworanti *et al.*, 2023). Research performed by Frigon et al. (2011) reported an increase of 29% and 42% in CH_4 production using manganese peroxidases and lignin peroxidases enzymes as a pretreatment of switchgrass (Frigon *et al.*, 2011).

15.4.3.4 Termite pretreatment

Termites, including species such as *Termes hospes*, *Microcerotermes parvus,* and *Nasutitermes ephratae*, are used to break down lignocellulosic materials due to their ability to secrete specific enzymes that degrade lignocellulose, thus facilitating the anaerobic digestion (Awogbemi and Kallon, 2022).

15.4.4 Physicochemical pretreatment

Physicochemical pretreatment methods are a strategy that merges the advantages of physical and chemical approaches to process lignocellulosic biomass. These techniques focus on addressing the fundamental challenges associated with the

conversion of lignocellulosic raw materials into useful products, such as lignin strength and cellulose crystallinity. Among the most prominent methods are extrusion pretreatment, steam explosion, alkaline-heat pretreatment, and ammonia fiber explosion (Awogbemi and Kallon, 2022).

15.4.4.1 Steam explosion pretreatment

Steam explosion involves the application of heat (160-260°C) and pressure (5 and 50 bar) to break bonds in lignin and modify the biomass structure, thus facilitating the release of useful components (Aworanti *et al.*, 2023; Naik et al., 2021). This approach is ideal for treating hardwood but can produce inhibitors at high temperatures (Naik, Poonia, and Chaudhari, 2021). While this method can be highly effective in reducing lignin and hemicellulose, its implementation may face challenges due to its high energy consumption and generation of inhibitory compounds (Awogbemi and Kallon, 2022).

15.4.4.2 Alkaline-heat pretreatment

Alkaline-heat pretreatment, on the other hand, uses temperatures in the range of 75 and 125°C and alkalis such as sodium hydroxide, alkaline peroxide, and sodium carbonate to decompose lignin and hemicellulose, thereby increasing the cellulose content available for conversion (Awogbemi and Kallon, 2022). Although effective, this method can be complex and costly to implement on a large scale due to the need to maintain high temperatures and the use of chemicals (Awogbemi and Kallon, 2022).

15.4.4.3 Ammonia fiber explosion pretreatment

Ammonia fiber explosion pretreatment involves the decomposition of bonds between hemicellulose and lignin through the synthesis of oxyhydrogen ions and ammonia at high pressure and temperature. This method has demonstrated effectiveness in breaking down lignin and improving glucose yields in materials such as corn stover and barley straw (Awogbemi and Kallon, 2022).

15.4.4.4 Extrusion pretreatment

Extrusion pretreatment combines mechanical and thermal techniques for modifying the composition of lignocellulosic biomass, with the addition of sodium hydroxide to enhance hemicellulose and lignin removal. These strategies are promising for improving biomass conversion into useful products but require further research to optimize their efficacy and feasibility on a large scale (Awogbemi and Kallon, 2022).

15.5 Operational methods and reactor designs

Anaerobic digesters vary in cost, design complexity, and materials of construction worldwide. For the design of any digester, it is essential to consider three aspects: that the geometry and materials of the digester allow for continuously handling a higher organic loading rate, that the volume and configuration of the system ensure the production of a high volume of high-quality biogas, and that the design optimizes the hydraulic retention time to minimize the size of the reactor (Korbag *et al.*, 2021). Therefore, several types of biodigesters are currently available in the bioenergy industry, such as batch, multistage, single-stage continuous, or two-stage systems. Other configurations include plug flow systems, the tubular reactor, the Anaerobic Sequencing Batch Reactor (ASBR), Anaerobic Baffled Reactor (ABR), and anaerobic filters (Korbag *et al.*, 2021). The selection of the most suitable reactor generally depends on the properties of the agricultural waste feedstock, especially the total solids content. High-sludge and solid-rich feedstocks are typically processed in CSTRs, whereas soluble organic wastes are mainly digested in UASB reactors, fluidized bed reactors, or anaerobic filters. Co-digestion is mainly performed in single-stage wet processes, such as CSTRs (Banerjee and Sivamani, 2022).

Continuous systems constantly feed and discharge digestate at a consistent rate, maintaining a steady state and constant gas production. However, this operational mode is suitable only for substrates that can be continuously pumped. Alternatively, semi-continuous processes with discrete feedings multiple times a day are used for substrates that cannot be pumped continuously. Continuous systems are advantageous because of their simple design and operation and low capital costs, but they have disadvantages such as rapid acidification and increased production of volatile fatty acids (VFA) (Banerjee and Sivamani, 2022).

15.5.1 Batch reactor

In anaerobic digestion, batch reactors are the easiest to operate as they are loaded with the agro-waste feedstock, mixed, and allowed to stand until empty, resulting in low capital cost. However, they can suffer from clogging and channeling, as

well as higher volume with lower biogas yield. CH_4 production is higher at the beginning and then decreases due to substrate consumption (Banerjee and Sivamani, 2022). Its advantages include technological simplicity, low maintenance and investment needs, and minimal energy losses (Mahmudul *et al.*, 2021).

15.5.2 Biofilm reactors

Biofilm reactors employ microbial consortia attached to support materials, which are usually suspended or fixed inert materials. In these systems, anaerobic microbial biofilms digest the organic materials to produce biogas. These reactors can handle high organic loads and adapt to fluctuations in both organic and hydraulic loads, thanks to the considerable mass of immobilized biofilm and the enhanced mass transfer of liquid around due to its movement. In comparison to other traditional anaerobic systems, biofilm reactors have shorter start-up times once the biofilm is formed. The adhesion and mechanical stability of biofilms are highly dependent on the support material used (Angelidaki *et al.*, 2018; Banerjee and Sivamani, 2022).

15.5.3 Anaerobic baffled reactor (ABR)

The ABR and its variant, the up-flow anaerobic sludge-bed reactor (UASBR), are effective systems for treating high-solids waste and are a feasible option in certain developing countries (Banerjee and Sivamani, 2022). Treatment can be improved by increasing the sludge contact time, which allows a wide variety of wastewater to be treated. However, sludge and effluent need further appropriate treatment before reuse or discharge (Korbag *et al.*, 2021).

15.5.4 Anaerobic plug flow reactors (APFRs)

APFRs are extended rectangular channels where the waste stream enters at one end and exits at the other, with little mixing along the flow. Typically situated at the surface, these channels operate under either thermophilic or mesophilic conditions (Banerjee and Sivamani, 2022). APFRs are considered high-efficiency digesters, commercially employed to treat various types of organic wastes, including animal manure waste.

15.5.5 Continuous flow stirred tank reactors (CSTR)

CSTRs are widely used as high-rate digesters for biogas production due to their simple design in contrast to other methane digesters (Korbag *et al.*, 2021; Banerjee and Sivamani, 2022). These reactors are commonly employed to treat sludge with total solids ranging from 5 to 10%, such as animal manure sludge and organic industrial waste (Banerjee and Sivamani, 2022). Despite their popularity, CSTRs have certain disadvantages, such as long retention times and higher energy consumption compared to other reactor types (Korbag *et al.*, 2021). However, the performance of CSTRs can be improved by increasing the retention of active biomass or by recycling microbial solids (Banerjee and Sivamani, 2022; Korbag *et al.*, 2021).

In the field of anaerobic digestion, CSTRs and plug flow reactors (PFRs) are the two most commonly used reactor types. CSTRs employ biogas recirculation for mechanical agitation or mixing of the effluent and are mainly used in wet digestion systems. On the other hand, PFRs involve the movement of reactor contents along a horizontal channel and are primarily employed in dry digestion processes for substrates with a high solids content (Korbag *et al.*, 2021). The selection between wet or dry digestion processes depends on the total solids content (TS) of the material to be digested. In developed countries, biogas production from manure is often performed using PFR and CSTR, covered lagoons, and some other types of anaerobic reactors (Banerjee and Sivamani, 2022).

15.5.6 Anaerobic contact reactor (ACR)

The anaerobic contact reactor (ACR) operates as a mechanically agitated tank system that includes sludge recycling. The effluent is sent to a solid-liquid separator, such as a settling tank, flotation device, or lamellar clarifier, to recover solids. These solids are then reintroduced into the anaerobic digester. Thanks to the high concentration of microbial activity, ACRs are effective in the treatment of resistant wastes with concentrated digestible solids. They have short hydraulic retention times and handle fluctuations in organic load well, being less susceptible to acidity and other inhibitors. Agitated digesters with membrane-based cell retention are efficient in biogas generation (Banerjee and Sivamani, 2022; Korbag *et al.*, 2021).

15.6 Factors affecting biogas production

As mentioned above, biogas generation consists of four complex biochemical stages, which depend on various physical and chemical factors such as temperature, pH, temperature, carbon-nitrogen (C:N) ratio, hydraulic retention time, and

mixing conditions (Uddin *et al.*, 2021). If these factors are not in a proper range, the anaerobic digestion process can stall or slow down (Sawyerr *et al.*, 2019). Therefore, it is crucial to control these parameters to optimize biogas production.

15.6.1 pH

The optimum pH value in the anaerobic process may change depending on the digestion technique used and the agricultural waste substrate. Therefore, maintaining a stable pH is crucial and is achieved by using buffering agents like calcium carbonate. The pH serves as a key indicator of system performance and digestion stability (Sawyerr *et al.*, 2019). There is a potential for microbial inhibition when the process is negatively affected by the decrease of pH (below 6 or exceeds 8.5). A low pH mainly indicates the culture media poor buffering capacity, which can inhibit digestion. On the other hand, pH increases through the elimination of CO_2 and the generation of ammonia during protein degradation, which may also hinder the methanogenesis process (Atelge *et al.*, 2020; Angelidaki *et al.*, 2018). The pH value is influenced by factors such as bicarbonate concentration, VFA concentration, system alkalinity, and fraction of carbon dioxide in the digester gas (Sawyerr *et al.*, 2019).

15.6.2 Temperature

Microorganisms present in anaerobic digestion can perform both thermophilic and mesophilic processes. Mesophilic and thermophilic bacteria in anaerobic digestion processes are efficient in a temperature range from 25°C to 40°C and from 45° to 80°C, respectively (Kabeyi, Olanrewaju, and Messineo, 2022). Although thermophilic digestion may have certain advantages compared to mesophilic digestion, such as pathogen reduction and higher reaction rate, microorganisms in mesophilic digestion require fewer nutrients, and the latter may operate similarly to thermophilic digestion. The decision between using a mesophilic or thermophilic temperature will depend on the desired objective. However, it is critical to employ a temperature that is compatible with the microorganisms used in waste treatment (Sawyerr *et al.*, 2019).

15.6.3 Hydraulic retention time (HRT)

The hydraulic retention time (HRT) is the average time that agricultural waste remains in the reactor, allowing its interaction with microorganisms (Sawyerr *et al.*, 2019). HRT is an essential factor as it defines the flow rate processed in the bioreactor (Mahmudul *et al.*, 2021). A shorter HRT may result in the accumulation of volatile fatty acids, which in turn alters pH, while a longer HRT generates higher methane content and higher biogas production (Mahmudul *et al.*, 2021).

15.6.4 C:N ratio

Carbon and nitrogen concentrations are crucial for anaerobic digestion performance, which usually occurs at an optimal C/N ratio ranging from 20:1 to 35:1 (Korbag *et al.*, 2021; Mahmudul *et al.*, 2021). Carbon provides energy for microorganisms, while nitrogen is essential for microbial growth. When nitrogen is limited, microbial populations remain small, slowing down the breakdown of carbon compounds, which reduces biogas production (Korbag *et al.*, 2021). At high C/N ratios, nitrogen is rapidly consumed, leaving an excess of carbon unused, leading to low biogas generation and yield. At low C/N ratios, excess nitrogen produces ammonia, increasing the pH above 8.5, which inhibits microbes and reduces biogas generation (Kabeyi, Olanrewaju, and Messineo, 2022; Korbag *et al.*, 2021).

15.6.5 Mixing

Mixing in a conventional anaerobic digester has several crucial benefits, such as balancing temperature and pH, avoiding solids and foam deposition, stratification, and creating a uniform biological, physical, and chemical environment. This improves contact between microorganisms and substrate and dilutes inhibitory substances, thus increasing biogas production. However, the mixing condition, whether continuous or discontinuous, can present challenges. Mixing can be classified into three main groups: mechanical pumping, mechanical stringing, and gas injection. The mechanical pumping system recirculates the substrate in the digester creating internal flow, although it can experience clogging issues. Mechanical stringing (the most common type) uses a propeller, paddle stirrer, or rod mixer, but one of the main disadvantages is component wear and maintenance costs. The gas injection system introduces biogas to mix the digester contents by rising gas bubbles. Mixing has been observed to generally increase CH_4 yields and stabilize the digester by minimizing hydraulic dead zones, as well as preventing the accumulation of unfavorable conditions such as low pH and high VFA levels. In addition, it helps to remove the CO_2 excess, which can have an inhibitory effect on the microbial consortia at high partial pressures (Sawyerr *et al.*, 2019).

15.7 Additives to enhance biogas production from agricultural wastes

The increasing demand for bioenergy has driven the need to improve the viability of the anaerobic digestion process and increase biomethane production. To achieve this, various additives have been employed to improve the performance of digesters. In the following, additives that enhance the hydrolysis, acid production, and methane production stages in anaerobic digestion are presented to optimize their use in agricultural waste processing (Gu *et al.*, 2024).

15.7.1 Additives to accelerate the hydrolysis process

As mentioned, hydrolysis is the slowest stage of the anaerobic digestion process. To improve the performance of anaerobic digestion, pretreatment methods using enzymes or microorganisms to speed up hydrolysis have been investigated. However, there is little research on their direct addition to the anaerobic digestion process. The incorporation of these enzymes or microorganisms can significantly promote the hydrolysis of organic matter, providing reactants for the next stage and speeding up the process, which improves the biogas yield (Gu *et al.*, 2024).

Biological enhancement through the addition of functional microorganisms to the anaerobic digestion system accelerates the hydrolysis of organic matter like cellulose, hemicellulose, and lignin present in the lignocellulosic biomass, thus improving the start-up rate of the system. It has been shown that the addition of hydrolytic bacteria such as *Bacillus* spp., *Pseudomonas* spp., and *Rhodococcus* spp. can improve the digestion of lignocellulosic biomass (Gu *et al.*, 2024; Li *et al.*, 2022). In addition, enzyme cocktails need to be used due to their specificity and adaptability to various temperature and pH conditions to significantly accelerate the hydrolysis step and degrade large molecules into more accessible nutrients for methanogenic bacteria, reducing the anaerobic digestion cycle and increasing biogas production. The most commonly used hydrolytic enzymes include lipases, amylases, cellulase, and proteases (Gu *et al.*, 2024).

15.7.2 Additives to maintain digestive homeostasis

To maintain a proper balance during anaerobic digestion and improve gas production, it is essential to control the concentration of organic acid and ammonia nitrogen, as their imbalance can threaten the digestive environment. To address this, inorganic substances are used to regulate the concentration of ammonia/nitrogen, as its accumulation can inhibit the digestion process. On the other hand, conductive materials are used to enhance the accumulation of volatile fatty acids, which can negatively affect the pH and, as a consequence, the bacterial activity. Examples of these additives are biochar and zero-valent iron, which enhance interspecies electron transfer and microbial metabolism (Gu *et al.*, 2024).

15.7.3 Additives that enhance biological metabolism

Another activity during the anaerobic digestion that is crucial to improve the process performance is the increase of metabolic activity in methanogenic bacteria, the main microorganisms involved in this process. Given the slow growth and activity cycle of these bacteria, additives are supplements to provide and make more accessible the necessary nutrients. Two common approaches are nutrient supplementation through micronutrient solutions, which influence the bacterial growth and its metabolic activity. Additionally, chelating agents such as citric acid, ethylenediaminetetraacetic acid (EDTA), and nitrilotriacetic acid (NTA) have been employed to improve nutrient availability. These agents can also form stable complexes with metals in the digestion system, thus improving its performance and gas production (Gu *et al.*, 2024).

15.8 Biogas upgrading

After anaerobic digestion, most agricultural residues are transformed into biogas, which is collected from the top of the reactors (Jameel *et al.*, 2024). Biogas primarily consists of CH_4 and CO_2, among other minor components like hydrogen sulfide, water, and ammonia (Mortier, Velghe, and Verstichel, 2016), which can be considered impurities depending on the biogas's final application (Tomczak *et al.*, 2024). Hence, it is necessary to understand their characteristics and upgrading technologies, as shown below.

15.8.1 Water vapor (H_2O)

Raw biogas typically contains a small proportion of water vapor (Rabinovich *et al.*, 2024). Upon leaving the AD bioreactor, biogas is saturated with water vapor to approximately 10% moisture content in thermophilic digestion and 4% in mesophilic digestion (Mortier, Velghe, and Verstichel, 2016). This moisture reduces the heat capacity of biogas, when combined with compounds such as H_2S and CO_2, and can accelerate corrosion, including the formation of sulfuric acid (H_2SO_4) when reacting with H_2S (Tomczak *et al.*, 2024). Therefore, the most common processes used to solve this

problem are the use of condensers and adsorption technologies that generally remove water from the raw biogas (Gadirli *et al.*, 2024).

15.8.1.1 Condensation

Condensation consists of cooling the biogas to remove water. This method is used in most existing biogas plants, often passively by piping gas through long pipes exposed to ambient temperature or buried to take advantage of the ground temperature. These pipes carry the gas to a condensate separator, which must be protected against frost and regularly emptied. The efficiency of passive cooling fluctuates based on external or ground temperatures. For more reliable cooling, the gas can be compressed to below the dew point and then decompressed to achieve the desired pressure, while removing condensed water using methods such as a cyclone filter, demister, or moisture trap compressor (Mortier, Velghe, and Verstichel, 2016; Tomczak *et al.*, 2024).

15.8.1.2 Adsorption

In this technique, biogas undergoes dehydration by passing it through a silica-based filter. Typically, two silica columns work simultaneously: one for adsorption and the other for regeneration. In addition to silica, activated carbon, magnesium, and aluminum oxides are also viable options for this purpose. Although it offers higher water removal efficiency than condensation, its use is less common because of the elevated operational costs associated with the adsorption materials (Francisco López *et al.*, 2024; Mortier, Velghe, and Verstichel, 2016).

15.8.2 Hydrogen sulfide gas (H_2S)

H_2S gas is a colorless, strong-smelling, flammable gas that is slightly heavier than air and has a molar mass of 34.08 g/mol. In raw biogas, H_2S is a significant impurity present at concentrations of up to 10,000 ppm, which has detrimental effects on the environment and human health. H_2S concentrations between 200 and 300 ppm can cause respiratory arrest (Tomczak *et al.*, 2024). This gas is the most common harmful impurity formed during the digestion of proteins and other sulfur-containing materials. Because of its high corrosiveness, it can cause damage to facilities and pipelines; therefore, it is necessary to remove H_2S early during the biogas upgrading process (Francisco López *et al.*, 2024; Sun *et al.*, 2015). Furthermore, H_2S can be combined with water vapor to form sulfuric acid, so it is crucial to remove this component from biogas before its use (Mortier, Velghe, and Verstichel, 2016). H_2S removal is also important to avoid the formation of sulfur dioxide (SO_2) when biogas is used as a fuel (Sun *et al.*, 2015). As a result, removing H_2S from biogas is crucial to ensure the safety of human health and the durability of the production and utilization infrastructure (Gadirli *et al.*, 2024). Conventional chemical treatments to remove H_2S like aqueous scrubbing with strong bases are not environmentally friendly because of the high chemical, energy, and waste disposal requirements. On the other hand, biological methods offer an environmentally safe alternative, although they are more expensive than chemical treatments (Tabatabaei *et al.*, 2020). Unlike chemical products, the end products of biological desulfurization are no longer hazardous. The choice of the appropriate removal technique depends on several factors, such as gas concentration, treatment cost, and H_2S content (Tomczak *et al.*, 2024).

15.8.2.1 Chemical removal of H_2S inside and outside of the AD reactor

The removal of H_2S inside of the digester can be directly removed by the addition of iron (Fe)-containing compounds to the input substrate or digestate in the digester. The reaction of Fe with sulfur produces iron sulfide (FeS). For dosing Fe, the most effective way is adding ferrous chloride ($FeCl_2$), although Fe-containing sludge or wastewater from treatment plants can also be used. However, the variable iron concentrations in these products make it difficult to maintain optimal H_2S removal. Nevertheless, the addition of iron to a reactor is a more economical option. In contrast to biological H_2S removal, iron addition provides greater reliability because sudden increases in H_2S production can be quickly counteracted by an increase in iron dosage (Mortier, Velghe, and Verstichel, 2016; Nägele *et al.*, 2017). Now, the removal of H_2S outside the digester is mainly by its adsorption with iron hydroxide ($Fe(OH)_2$) or ferric oxide (Fe_2O_3) results in the formation of iron sulfide (III) (Fe_2S_3). Typically, wood chips are impregnated with iron oxide to obtain high surface/volume ratios. This reaction requires a minimum temperature of 12°C but is optimal between 25°C and 50°C (Khan *et al.*, 2021; Paglini, Gandiglio, and Lanzini, 2022). Another method is adsorption using liquid solutions of sodium hydroxide (NaOH), iron chloride ($FeCl_2$), or ferric oxyhydroxide ($Fe(OH)_3$), where the biogas and liquid are mixed in a counter-current system (Khan *et al.*, 2021; Paglini, Gandiglio, and Lanzini, 2022). Alternatively, adsorption can be performed using activated carbon treated with potassium iodide (KI) or sulfuric acid (H_2SO_4). This method is effective under

conditions of 7 to 8 bar pressure and temperatures ranging from 50°C to 70°C. Finally, the activated carbon regeneration is achieved using hot nitrogen (N_2) gas or steam (Mortier et al., 2016). Semi-permeable membrane separation to separate H_2S from CH_4 and CO_2 is another suitable method (Francisco López *et al.*, 2024).

15.8.2.2 Biological removal of H_2S

The biological removal of H_2S in the AD reactor involves the oxidation of H_2S to elemental sulfur or liquid sulfuric acid by specialized bacterial strains, such as the aerobic group *Thiobacillus* sp. These bacteria require support such as a specifically designed structure, floating layer, or the reactor walls to grow in the reactor. Although this technology is simple and inexpensive, its regulation is difficult because of the sensitivity of bacteria to sudden changes in H_2S levels. In addition, oxygen dosing can generate a locally explosive gas mixture; therefore, air injection pipes must be placed on the opposite side of the biogas outlet pipes. Accidental reintroduction of elemental sulfur into the reactor can result in anaerobic conversion to H_2S, which can negatively affect the biology of the system (Mortier, Velghe, and Verstichel, 2016).

The efficiency of this process depends on the bacterial activity of chemolithotrophic or photoautotrophic bacteria that oxidize sulfur. Chemolithotrophic oxidation of H_2S is usually performed by microorganisms that obtain energy from the oxidation of sulfur compounds, mainly those from the *Thiobacillus, Thiomicrospira, Thiothrix, Beggiatoa,* and *Achromium* genres (Tabatabaei *et al.*, 2020). Photoautotrophs have also been investigated to enhance the biological removal of H_2S, as well as chemical-biological systems, at pilot and laboratory scales to treat high concentrations of this compound (Tabatabaei *et al.*, 2020). Another promising alternative is microalgae-bacteria symbiosis in photobioreactors, which allows the simultaneous removal of CO_2 and H_2S from biogas. These innovative technologies may boost the use of biological approaches over the chemical methods, reduce costs, and improve sulfide removal efficiency (Tabatabaei *et al.*, 2020).

15.8.3 Carbon dioxide

CO_2 is a colorless gas with a molecular weight of 44.01 g/mol and approximately 1.5 times heavier than air at room temperature. In raw biogas, CO_2 is a significant contaminant whose concentration varies depending on factors such as the pressure, temperature, and liquid content in the digester (Tomczak *et al.*, 2024). Typically, its concentration is between 30% and 45% by volume. Although nontoxic, CO_2 reduces the calorific value of biogas, laminar flame speed, density, and combustion efficiency, which limits its application to heat and power generation, affecting its economic viability (Tomczak *et al.*, 2024).

When biogas is injected into the natural gas grid or as a vehicle fuel, it is necessary to remove all or most of the CO_2 present. However, the equipment to remove CO_2 is very sensitive, and the removal of water and H_2S is required previously (Mortier, Velghe, and Verstichel, 2016). In addition, CO_2 can cause corrosion in piping and wear the installation equipment (Tomczak *et al.*, 2024). Capturing CO_2 from biogas not only reduces emissions but can also contribute to halting global warming, with positive impacts on the environment and human health (Tomczak *et al.*, 2024). Likewise, the removal of CO_2 from biogas has several advantages like a 30% improvement in the calorific value of the produced biogas (5,300 kcal/m^3 vs. 6,800 kcal/m^3). Furthermore, CO_2 removal can lead to a reduction in the costs of compression and transport. After CO_2 removal, biomethane possesses properties identical to purified natural gas. As a result, the final anaerobic digestion product can be used as a biogenic replacement for fossil-based natural gas in various industries (Tabatabaei *et al.*, 2020). In addition, the use of technologies such as adsorption, membrane, and cryogenic separation as well as biological methods are currently available for CO_2 removal.

15.8.3.1 Adsorption

A wide technique used to separate CO_2 from biogas is via high-pressure scrubbing. In this technology, a packed bed enhances contact between the water entering the scrubbing tower from the top and the biogas fed from the bottom at 10-20 bar. As CO_2 is more soluble than CH_4, the biogas leaving the column becomes enriched with CH_4. Pressure swing adsorption (PSA) and vacuum pressure swing adsorption (VPSA) employ a molecular sieve like activated carbon to adsorb CO_2 while allowing CH_4 to pass through. This process operates cyclically, with adsorption occurring at high pressure and desorption (regeneration) at low pressure. H_2S irreversibly binds to the molecular sieve and must therefore be removed beforehand to avoid contamination/saturation of the activated carbon (Mortier, Velghe, and Verstichel, 2016).

15.8.3.2 Membrane separation

Membrane separation utilizes the selective permeability of membranes to separate CH_4 and CO_2. To obtain a CH_4-rich gas and minimal CH_4 loss, there must be a substantial difference in permeability between the two gases. This separation

process operates based on two principles: high-pressure membrane separation, which involves gas phases on both sides of the membrane, and low-pressure membrane separation, where permeated molecules are adsorbed onto a liquid phase (Mortier, Velghe, and Verstichel, 2016).

15.8.3.3 Cryogenic separation

Due to the differing condensation temperatures of CO_2 and CH_4, biomethane can be separated by cooling and compressing it, until obtaining liquid CO_2 that can be easily separated from the remaining CH_4 gas. This technology produces high-purity CO_2 gas, suitable for a variety of applications (Mortier, Velghe, and Verstichel, 2016).

15.8.3.4 Biological CO_2 removal technologies

Bio-electrochemical systems utilize living microbes in microbial electrolysis cells (MECs) for upgrading biogas by converting CO_2 to CH_4 or capturing CO_2 for other applications or self-sustaining catalysts with microbes. The bio-electrochemical process of CO_2 removal involves electro-methanogenesis or hydrogenotrophic methanogenesis processes (Tabatabaei *et al.*, 2020). Additionally, microalgae CO_2 absorption can be harnessed to improve biogas production. Microalgae possess the ability to sequester substantial quantities of CO_2 due to their rapid growth rate and ability to thrive in diverse environmental conditions. The biomass produced through CO_2 valorization in microalgae holds potential as a feedstock for synthesizing additional biofuels or creating value-added products (Tabatabaei *et al.*, 2020).

15.8.4 Other impurities

In addition to CO_2 and H_2S, biogas can contain various impurities, such as siloxanes, oxygen (O_2), and nitrogen (N_2), which can cause damage to the distribution system and use (Sun *et al.*, 2015). Although O_2 and N_2 are not natural components of biogas, they are sometimes present. Typical levels of N_2 and O_2 in raw biogas are generally up to 15% and 3%, respectively (Mortier *et al.*, 2016). The presence of N_2 in raw biogas is considered to indicate problems such as denitrification or an air leak in the reactor, which, although not having an adverse environmental impact, reduces the calorific value of biogas (Tomczak *et al.*, 2024). The detection of O_2 in the raw biogas suggests the entry of air into the digester, which leads to the formation of compounds such as water, hydroxides, and oxides, which can generate explosion risks at concentrations above 6% v/v, depending on the temperature (Tomczak *et al.*, 2024). This must be addressed to prevent the formation of an explosive gas mixture. The presence of air in biogas occurs more frequently in landfill gas reactors than in anaerobic digestion reactors (Mortier *et al.*, 2016). Removing both O_2 and N_2 using membranes or pressure swing adsorption (PSA) is costly, and preventing its entry/formation into the system is preferable as a cheaper and more reliable alternative is always recommended (Mortier, Velghe, and Verstichel, 2016).

Minor impurities such as siloxanes are commonly found in landfill biogas production processes, especially from household waste, and are noxious to the process because they can damage engines. Activated carbon, cryogenic separation, or polydimethylsiloxane (PMDS) membranes are viable methods, although periodic replacement of activated carbon due to irreversible binding with siloxanes can be costly (Mortier, Velghe, and Verstichel, 2016). Finally, the technology selection for biogas upgrading is not only limited to cost minimization but must also meet the gas quality requirements for its intended use. A detailed analysis of each biogas cleaning and upgrading technology, along with the gas quality requirements for various applications, is critical for the appropriate choice (Sun *et al.*, 2015).

15.9 Biogas applications

As described in this chapter, the primary output of anaerobic digestion is biogas, consisting predominantly of CH_4 (60-70%) and CO_2 (30-40%), and low concentrations of other gases. In this context, both methane fuel biogas and carbon dioxide can be used in various applications to maximize the economic and environmental viability of AD from agricultural waste (Tabatabaei *et al.*, 2020)

Biogas derived from agro-waste is a promising option for energy generation in various settings, such as the decentralized generation of electricity in rural areas, where biogas is considered a valuable renewable energy source (Singh *et al.*, 2023). In numerous rural areas around the world, traditional cooking practices often depend on biomass fuels, such as charcoal and wood, which can detrimentally impact both health and the environment (Singh *et al.*, 2023). In addition, small-scale biogas plants can generate electricity, benefiting not only households but also schools and health centers in rural communities. This helps in closing the energy access gap and enhancing the quality of life in marginal areas (Singh *et al.*, 2023).

Biomethane has applications in gas heaters, cookers, vehicle fuel, or industrial heating and power production after being properly purified. In this regard, biogas also has significant potential as a vehicle fuel, thus reducing the dependence on imports of conventional fuels. The use of agricultural residues and other domestic biomass sources as feedstock in biogas production can be transformed into electrical energy to drive motors for generators and pump sets (Singh *et al.*, 2023). Upgraded biogas can also be safely blended with compressed natural gas (CNG) and utilized as a fuel for engines, offering reliable engine performance and lower emissions (Singh *et al.*, 2023). As a result, biogas obtained from agricultural wastes can be used within several systems for heating, industrial power generation, and biomethane injection into natural gas grids (Ankathi *et al.*, 2024).

Digestate, the residue from anaerobic digestion of agricultural wastes and livestock byproducts (Mignogna *et al.*, 2023), holds promising applications in agriculture. Specifically, it can serve as an organic fertilizer to replace chemical fertilizers in agricultural practices (Khalil *et al.*, 2019; Tabatabaei *et al.*, 2020). Given the wide variety of substances and the wide range of compounds contained in digestate, its direct use as a fertilizer is the main recommended use for its management. The resulting digestate had a higher moisture content than the initial biomass due to biological degradation during biogas production. The residual organic matter is stable and contains essential nutrients like potassium, phosphorus, and nitrogen, which can be returned to the soil and support crop growth. Digestate is valued for its high organic content and nutrient richness, potentially enhancing soil health and crop yields and reducing reliance on chemical fertilizers, thus promoting sustainable agriculture (Singh *et al.*, 2023). Moreover, digestate is reported to enhance soil fertility by increasing humic substance levels, thanks to its organic matter, vitamins, amino acids, and beneficial microorganisms. Its use for plant fertilization allows diversification and increases the economic efficiency of agricultural activities. However, the physicochemical properties of digestate vary significantly based on the nature and composition of feedstock and digestion process parameters. Likewise, digestate contains pathogens, odors, and other pollutants that have a negative impact, especially if the digestate is used excessively. It might alter the soil ecosystem or have a direct impact on plant growth through its heavy metals such as Ni, Cr, Cd, As, Cu, Pb, and Zn and GHG emissions. Therefore, proper management of digestate before its safe release into the environment is crucial (Mignogna *et al.*, 2023). Effective treatment methods and sustainable strategies are essential for managing digestate and maximizing its environmental benefits. Finally, a circular economy can be established by recovering and commercializing all the main and byproducts of anaerobic digestion. This would contribute to addressing food and energy needs, while mitigating greenhouse gases and providing social benefits through job creation (Tabatabaei *et al.*, 2020).

15.10 Global overview of biogas production

The imperative for energy security and sustainability has significantly transformed the global bioenergy landscape (Sidi Habib and Torii, 2024). The history of biogas use as an energy source dates back to 1859, when Sir William Thomson identified methane production from organic matter in a closed vessel (Gadirli *et al.*, 2024). In the early 20th century, the first biogas plant was established in India and used for lighting and cooking. Today, biogas production has been adopted globally not only for its environmental benefits but also for its efficiency in converting waste to energy (Gadirli *et al.*, 2024). For instance, between 2000 and 2017, global biogas production increased from 78 to 364 TWh, reaching a total global volume of 61 billion cubic meters per year. This four-fold increase was a consequence of supplying markets and users like transportation, heating, and electricity (Bórawski *et al.*, 2024; Tabatabaei *et al.*, 2020). The value of the global biogas market is expected to increase by 2025, driven by the increasing global demand for renewable energy, making biogas production a promising solution for sustainable energy generation (Gadirli *et al.*, 2024).

Over the past 20 years, biogas production has considerably expanded in Europe, North America, and Asia. However, Germany, China, and the United States led the way in terms of production capacity (Gadirli *et al.*, 2024). Europe led to biogas production, with 30.3 billion m^3 produced in 2018, followed by Asia with 19.3 billion m^3, and America with 8.34 billion m^3. Figure 15.3 shows the global biogas market using agricultural residues as a main feedstock (Gadirli *et al.*, 2024).

As mentioned, global production of biogas is estimated at 59.0 TWh/year, of which Europe contributes more than 50% (26.2 TWh/year). According to the European Biomass Association, the European Union has a production potential of 465 TWh, which is equivalent to 40 million tons of fossil oil (Tabatabaei *et al.*, 2020). In this context, biogas production plays a crucial role in achieving the European Union's renewable energy targets. Production is led by Germany, the United Kingdom, the Czech Republic, Italy, and France, as well as by the Scandinavian countries (Gadirli *et al.*, 2024). Agricultural and animal slurry residues have been particularly favorable for the European energy market (Bórawski *et al.*, 2024). In Germany, strong institutional and legal support, coupled with technological advances and the establishment of partnerships between farmers, enabled the country to occupy a 61% share in Europe, with more than 7,000 plants in 2010,

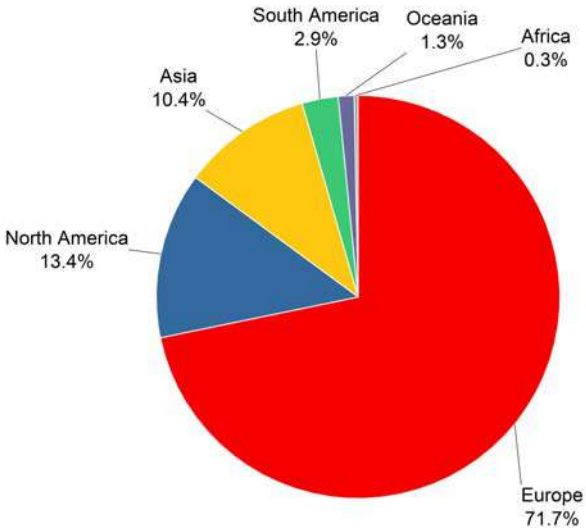


FIGURE 15.3 **Biogas production capacity around the world.** *Adapted from Singh et al. (2023).*

of which 84% use animal and agricultural residues (Gadirli *et al.*, 2024). In general, European biogas plants use agricultural residues, energy crops, and brewery or distillery wastes as feedstock. Finally, the resulting biogas is used for transportation, heat and power generation, or transformation into biomethane to later be blended into the gas networks (Bórawski *et al.*, 2024). In Asia, China and India have the largest biogas production with technically simple facilities. China has more than 100,000 biogas plants and a large number of domestic biogas units, resulting in approximately 40 million operating units. Additionally, Japan and Korea have a biogas market comparable to Western Europe, known for its dynamic and advanced technological landscape. In contrast, Bangladesh faces challenges in biogas development, including an immature biogas market, a lack of awareness of efficient biowaste utilization, and low political support (Gadirli *et al.*, 2024). In America, the United States is the major producer of biogas. Only in 2021, the value of its biogas market was $60.06 billion, and it is still developing with growing demand. One of the main reasons for this growing market is the favorable regulatory and political support, as well as geopolitical, environmental, and economic factors stemming from the agricultural industry (Bórawski *et al.*, 2024).

Finally, biogas still has to face technical, environmental, institutional, sociocultural, economic, and market challenges, and there is a possibility that biogas production may decrease in the future due to environmental issues, reduced employment in agriculture, and intense global competition for agri-products (Tabatabaei *et al.*, 2020). Furthermore, some barriers that hinder the advancement of the biogas market are the high investment cost, lack of knowledge and optimization of biogas plants, lack of government support, and low prices of natural gas (Ankathi *et al.*, 2024). Therefore, the implementation of government policies that support the transition and adoption of biogas as a renewable energy source derived from agricultural waste.

15.11 Biogas benefits and limitations

Anaerobic digestion of agricultural waste to produce biogas presents numerous advantages compared to other bioenergy production technologies and has been recognized as a highly energy-efficient and environmentally friendly technique for bioenergy production (Korbag *et al.*, 2021). There are many reasons why it is a versatile renewable energy source that make it the future of sustainable energies.

Agricultural waste management and valorization are several methods, approaches, and technologies aimed at efficiently handling and harnessing the generated wastes (Ufitikirezi *et al.*, 2024). The main benefits of anaerobic digestion technology are the transformation of agricultural waste into a valuable renewable resource, thereby reducing waste and generating green energy (Ufitikirezi *et al.*, 2024). Likewise, the use of agricultural waste as a feedstock for energy production helps to solve waste management problems and contributes to environmental management in the rural sector. On the other hand, biogas can also be used for co-generation of electricity and heat. Therefore, it can be used in small rural or marginal areas for lighting, heating, and cooking (Korbag *et al.*, 2021; Singh *et al.*, 2023). The use of agricultural residues in biogas production significantly reduces the amount of CH_4 released from open decomposition processes (Singh *et al.*, 2023). In addition, biogas production also contributes to food security as an alternative to energy crops eliminating the

competition between food production and bioenergy generation. In this sense, additional agricultural land is not required, thus mitigating deforestation as well as land use and the changes associated with agricultural expansion (Flores *et al.*, 2024; Francisco López *et al.*, 2024).

Various agricultural renewable wastes can be continuously supplied for anaerobic co-digestion under controlled conditions. The resulting biogas can be easily stored and upgraded to biomethane, which has a high calorific value and might replace natural gas (Korbag *et al.*, 2021; Singh *et al.*, 2023). Moreover, biogas serves as a versatile energy source for vehicles and industrial processes, facilitating heat and electricity generation (Korbag *et al.*, 2021). The residual agricultural waste can also be beneficially returned as digestate to the agricultural industry (Singh *et al.*, 2023; Ufitikirezi *et al.*, 2024). This technology is essential for supporting a closed cycle of atmospheric CO_2 fixation through photosynthesis (Flores *et al.*, 2024), as shown in Figure 15.4. Environmentally, biogas production holds significant promise in improving air quality, mitigating GHG emissions, climate change, global warming, and eutrophication (Korbag *et al.*, 2021). Furthermore, in social and economic terms, it contributes to strengthening the bioeconomy and creating jobs within the bioenergy sector, enabling farmers to sell biogas to the grid and commercialize digestate (Korbag *et al.*, 2021; Singh *et al.*, 2023).

Despite its recognition as a clean bioenergy alternative, biogas faces several important challenges (Singh *et al.*, 2023). First, the seasonality and long-term supply of agricultural residues, quantity, variability, and suitability for anaerobic digestion, logistics, and transportation must be considered (Flores *et al.*, 2024; Belinska *et al.*, 2024). On the other hand, the efficiency of anaerobic digestion and its dependence on the variable composition of the feedstock and its pretreatment must be considered due to the specific needs of the microorganisms involved, affecting the quality and quantity of biogas (Korbag *et al.*, 2021; Ufitikirezi *et al.*, 2024). In addition, variations in temperature or climate, pH, and acidity also influence microbial growth and functionality (Das *et al.*, 2023); therefore, controlling these operational parameters might represent an additional complexity, especially in cold regions, because thermal energy is required to maintain a constant

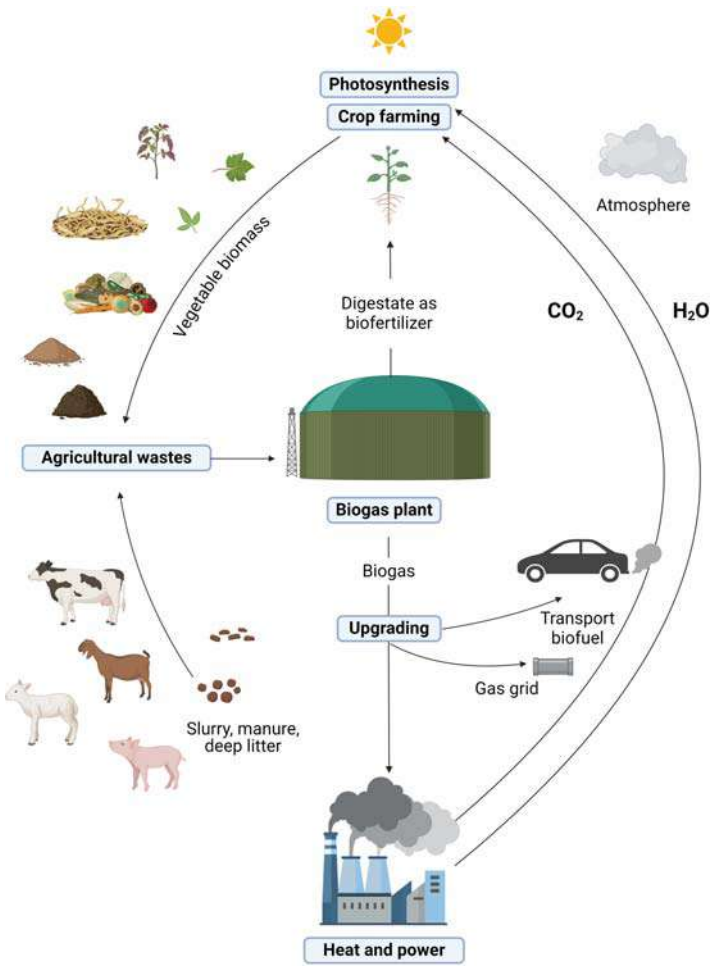


FIGURE 15.4 **Circular concept of agricultural wastes harnessing through anaerobic digestion.** *Adapted from Ankathi* et al. *(2024).*

supply of biogas (Korbag *et al.*, 2021; Singh *et al.*, 2023). Post-treatment also entails considerable energy consumption and high costs, while less expensive treatments are also less efficient (Belinska *et al.*, 2024; Francisco López *et al.*, 2024; Korbag *et al.*, 2021). Furthermore, the implementation and operation of new biogas production facilities have barriers, including high initial investment and high costs of equipment and materials for plant construction. Thus, the cost-effectiveness and scalability of biogas as a renewable energy source are limited by persistent competition from conventional energy sources, which frequently appear more economically viable in the short term (Singh *et al.*, 2023).

Finally, the social acceptance of biogas is often affected by environmental and health concerns (Singh *et al.*, 2023). The development of biogas has been unequal in different parts of the world, as it relies not only on the availability of feedstock but also on the presence of policies that encourage its production and use (Calero *et al.*, 2023). Variability in legislation and government policies also influences the viability and development of biogas as a renewable energy source. To achieve sustainable biogas energy exploitation, it is necessary to invest in both advanced production technologies and demand creation through measures that promote its use in a competitive energy market, where nonrenewable options are often more profitable (Singh *et al.*, 2023). Therefore, governments must increase awareness among farm owners to convert agricultural waste into valuable products, which will ensure a steady and sustainable flow of cost-effective feedstock for biogas production (Ufitikirezi *et al.*, 2024).

15.12 Future perspectives

Biogas is a promising form of renewable, sustainable, and clean energy derived from agricultural waste in the context of a circular economy (Francisco López *et al.*, 2024). This demonstrates the potential of replacing fossil fuel-based energy sources (Francisco López *et al.*, 2024) and reducing greenhouse gases, global warming effects, and environmental problems (Devi *et al.*, 2024).

Developing not only efficient and cost-effective bioconversion methods but also addressing transportation and storage issues and ensuring the sustainability throughout the entire chain are key areas of future research and development in the field of renewable energy for climate change mitigation (Das *et al.*, 2023). Over the last two decades, research has focused on new and more efficient technologies to improve sustainability and decrease operational costs, which are crucial for anaerobic digestion units (Francisco López *et al.*, 2024). Furthermore, the need to design and make more reliable bioreactors and their configurations, the use of chemical and biological additives, and the development of technologies for biogas upgrading need to be improved (Devi *et al.*, 2024). Although the current production process has proven to be effective in providing high-quality biogas, it still consumes a lot of energy and resources, and, in some cases, the captured CO_2 is released into the environment (Francisco López *et al.*, 2024). Therefore, future advances should be directed toward the development of more cost-effective, efficient, and standardized plants, which will strengthen the development of a circular economy based on agricultural waste (Francisco López *et al.*, 2024). Furthermore, future research should focus not only on reducing costs and improving efficiency but also on economic and environmental challenges. For instance, green or industrial lung, also called "enzymatic carbon dioxide capture," is an example of biomimicry that could be applied to biogas upgrading. This enzymatic process can be used to improve the efficiency of gas separation in membranes. However, it is necessary to identify and characterize new supports for enzyme immobilization, design continuously operating reactors, and reduce the general costs (Francisco López *et al.*, 2024).

The fundamental role of microorganisms in the decomposition and transformation of agricultural waste into biogas must be better understood and improved to increase the biogas yield in future production plants (Das *et al.*, 2023). The emerging trend of using synthetic biology and metabolic engineering tools to design new microbial strains and consortia with improved biogas production capabilities should be applied in the future. Genetic and metabolic engineering techniques allow for the modification and enhancement of microbial metabolism for the production of biogas from agro-wastes. These engineered strains are valuable not only for the pretreatment phase, but also for the biogas production and upgrading stages using agricultural waste as a feedstock. In addition, microbiomes from extreme environments can be a source to identify potential microbes that can be integrated into biogas production (Das *et al.*, 2023).

In contrast, the CH_4 and CO_2 produced can be harnessed to generate other forms of renewable energy. CH_4, through a steam reforming process, can be converted into a synthesis gas, which is a mixture of carbon monoxide and hydrogen. Syngas serves as a versatile feedstock for producing hydrogen or transforming into synthetic liquid fuels through Fischer-Tropsch synthesis. Additionally, microorganisms such as *Clostridium* sp. are capable of converting syngas into acetic acid, a useful product for various industries (Das *et al.*, 2023). In addition, certain anaerobic microorganisms such as *Clostridium ljungdahlii*, *C. carboxidivorans*, *C. autoethanogenum*, *Oxobacter pfennigii*, *Alkalibaculum bacchii*, and *Butyribacterium methylotrophicum* can utilize CO/CO_2 under anaerobic conditions to produce ethanol or butanol, which can be used in the production of advanced biofuels (Das *et al.*, 2023).

To maximize the potential use of agricultural residues, it is crucial to continue research and development focused on optimizing existing technologies, improving their efficiency, and exploring new applications. Per Agriculture and Technology 4.0, incorporating advanced technologies such as artificial intelligence, machine learning, and the Internet of Things (IoT) will be essential for improving multiple aspects of the biogas conversion process from agricultural waste. These advanced technologies can optimize time management, cost efficiency, and labor requirements, which in turn may increase the conversion efficiency and the quality of the final product. The implementation of these technological improvements will require significant interdisciplinary research and cooperation between academia, industry, and policymakers (Ufitikirezi *et al.*, 2024). Furthermore, to boost the development and use of agricultural waste-based energy in rural areas, the implementation of policies that promote the development of infrastructure and the corresponding training on the correct use and exploitation of agricultural waste biomass into energy is required. Continued incentives and policy support, such as feed-in tariffs, carbon pricing mechanisms, and renewable energy credits, may create a favorable market environment to support biogas production. Finally, governments and regulators are essential in establishing a supportive framework that promotes the advancement of biogas technologies, attracting investments, and fostering market growth.

15.13 Conclusion

Among the technologies for converting agricultural waste into gaseous energy products, anaerobic digestion represents a promising solution to current energy and environmental challenges. The generation of gaseous products such as biomethane and hydrogen contributes to the diversification of energy sources, promoting sustainability and their importance in the energy transition. These renewable gaseous fuels derived from agricultural waste can be integrated into industrial processes, which is crucial for a future low-carbon economy. Additionally, this not only valorizes agricultural wastes but also manages their disposal, which might otherwise release greenhouse gases into the atmosphere. Therefore, this technique promotes a circular economy within which different products and byproducts may return to the agricultural sectors, such as digestate when applied as a biofertilizer. However, effectively implementing waste-to-energy technologies requires greater technological innovation, favorable government policies, and collaboration between public and private sectors. Future research should focus on improving both biotic and abiotic parameters of the biogas production process from agrowaste to successfully scale up technologies from the laboratory to large-scale applications. This will maximize the utilization of this renewable waste and its conversion into valuable gaseous fuels for a greener future.

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Chapter 16

Industrial applications of agricultural waste for value-added products

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Chapter Outline

16.1. Introduction 253
16.2. Conversion of agro-waste into environmentally benign industrial products 254
16.3. Achieving SDGs through agro-waste innovations 257
16.4. Assessment of the bioenergy potential of agriculture waste 258
16.5. Conclusion 261
Acknowledgment 261
References 261

16.1 Introduction

In the realm of industrial applications of agriculture waste for value-added products, the concept of transitioning from a linear economic model to a more sustainable, integrated one is pivotal. However, differing interpretations of the circular economy among organizations and researchers have led to inconsistencies, hindering effective implementation. It is essential to address the current confusion surrounding the definitions of circular economy, bioeconomy, and circular bioeconomy to clarify misunderstandings among stakeholders (Tan and Lamers, 2021). Keeping this in mind, various sustainable practices from multiple sources, including aquaculture, livestock, crop residues, and agricultural industries, have emerged as a pressing challenge in waste disposal and management. Yet, amid this challenge lies a hidden treasure trove of organic riches—hemicellulose, lignocellulose, and lignin—laden with potent energy (Kaur and Sarao, 2021).

Technological strides have paved a promising avenue for transforming agricultural waste into a repertoire of value-added products, thereby fostering a circular economic ethos. This transformation not only mitigates waste accumulation but also fosters resource efficiency and environmental sustainability. Within this paradigm shift, the discourse revolves around the synthesis of eco-friendly solutions from agricultural waste, heralding a new era of innovation and sustainability (Brandão, Gonçalves, and Santos, 2021).

Delving deeper, this chapter critically examines the spectrum of eco-conscious products derived from agricultural waste: biodegradable plastics, bio-composites, bio-stimulants, bio-fertilizers, and biomedical materials. These products not only serve as alternatives to conventional counterparts but also herald a paradigm shift toward greener industrial practices. Moreover, agricultural waste finds itself repurposed across diverse industrial domains, spanning environmental remediation, wastewater treatment, and as a burgeoning source of green energy (Perumal *et al.*, 2022; Nida, Moses, and Anandharamakrishnan, 2020; Gupta and Mondal, 2019; Mostafa *et al.*, 2018).

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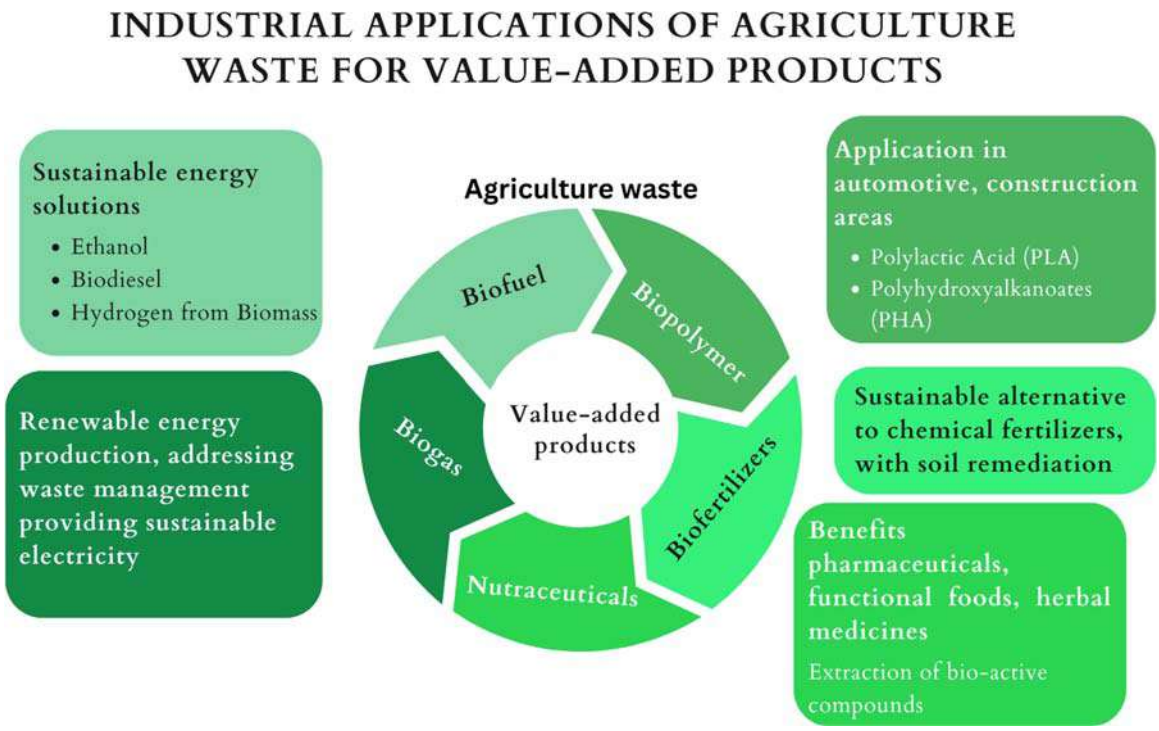


FIGURE 16.1 A cohesive approach to achieve sustainable industrial applications of agricultural waste biomass. Industrial applications of agricultural waste for value-added products.

Central to this narrative is the pivotal role of agricultural waste in addressing the pressing challenges of the 21st century, aligning with sustainable development goals and fostering a harmonious coexistence between industrial expansion and environmental preservation (Sporchia *et al.*, 2024). This chapter serves as a comprehensive compilation, delineating recent advancements in agricultural waste management practices that not only boost environmental security but also cater to the escalating energy demands of a burgeoning global population (Figure 16.1). Bioenergy derived from agricultural waste contributes to several Sustainable Development Goals (SDGs) that align with affordable and clean energy and responsible consumption and production, ultimately advancing circular economy principles and environmental sustainability.

Bioenergy is a form of renewable energy that is produced from organic matter. Agricultural waste has huge energy potential, and the mass of crop residues determines the residue-to-product ratio (RPR), which can be compared to other factors like surplus availability factor. The surplus recoverability of the crop waste available for bioenergy production and not being used for other purposes like animal fodder or bedding, feed, or bio-fertilizer prioritizes its potential in circular economy (Tanyi and Adaramola, 2023). The reuse of agro-waste into alternative raw materials for value-added products saves environmental damage and production costs as well. In summary, achieving sustainable industrial applications of agriculture waste for value-added products requires a cohesive approach that embraces circular economy principles, fosters innovation in biorefining technologies, and promotes the responsible utilization of natural resources. These eco-friendly products play a significant role in enhancing the economy by utilizing waste materials effectively and promoting sustainability in various industries.

16.2 Conversion of agro-waste into environmentally benign industrial products

16.2.1 Biomedical material

Recycled nanomaterials (RNMs) derived from agricultural waste have diverse biomedical applications because of their distinctive properties, including high stability, low toxicity, affordability, small size, and high biocompatibility (Nasrollahzadeh *et al.*, 2021; Esposito Corcione *et al.*, 2021). Carbon quantum dots (CQDs) derived from agriculture waste have

been extensively utilized in fluorescence imaging, drug delivery, cancer therapy, and tumor detection (Hua, Bao, and Wu, 2018; Chen *et al.*, 2021). For instance, CQDs derived from onion peel are used for imaging HFF and MG63 cells, and these biogenic CQDs exerted high biocompatibility and substantial wound-healing activity (Bankoti *et al.*, 2017). RNPs derived from fruit peel biomass are widely used in drug delivery and preparation of nano-vaccines (Bano *et al.*, 2016). CQDs obtained from sugarcane bagasse exhibit tremendous drug-loading capacity (Chung *et al.*, 2020).

RNMs derived from agriculture waste such as watermelon rind, citrus peel, and rapeseed oil cake exhibit strong antimicrobial activity through metal ion release and generation of oxidative stress (Wang, Hu, and Shao, 2017). RNMs derived from green tea waste, *Punica* peel, and *Abroma* bark exerted strong antioxidant activity (Mohamad Sukri *et al.*, 2019; Murru, Badía-Laíño, and Díaz-García, 2020; Das, Bag, and Basu, 2015). CQDs obtained from *Andrographis paniculata, Allium fistulosum,* and *Nerium oleander* biomass exhibit significant anti-cancer activity against breast cancer cell (MCF7), leukemia cells (K562), and HUVECs (Naik *et al.*, 2021). Gold nano-particles obtained from onion leaf extract and CQDs derived from bamboo leaf biomass were used to deliver an anti-cancer drug (DOX) in tumor cells (Patra, Kwon, and Baek, 2016; Fahmi *et al.*, 2018).

Hemp bioplastic composite derived from hemp shives waste, which has strong antibacterial activities, high durability, prodigious mechanical properties, good thermal insulation, and stiffness is an excellent biological material for the production of biomedical prototypes (Calì *et al.*, 2020). Anthinarayanan et al. (2015) reported the synthesis of biogenic silica nanoparticles (SNPs) from rice husks and concluded that these biogenic SNPs can be effectively utilized in bone tissue engineering. The green okra extract obtained from fermented soybean extract exerted strong antioxidant, superoxide, and nitric oxide scavenging activity (Gupta and Chen, 2019).

Recently, Gao *et al.* (2022) demonstrated that the peanut shells increase the neurite outgrowth of neuronal cells through synergistic interaction with the neurotrophic factors, thereby suggesting that peanut shell waste could be cost-effectively recycled for the production of commercially valuable nutraceutical products. Several studies have reported the extraction of bioactive compounds such as flavonoids, phenolic compounds, carotenoids, and nutrients (minerals, vitamins, and essential elements) from fruit, cereal, and vegetable manufacturing waste material (Kurnik *et al.*, 2018; Mirabella, Castellani, and Sala, 2014; Fuentes-Alventosa *et al.*, 2013).

16.2.2 Bio-stimulants and bio-fertilizer

Bio-stimulants are eco-friendly substances produced from natural bioresources that boost plant growth, crop quality, and productivity through enhanced nutrient uptake, better nutrient use efficiency, and stress tolerance (Abou Chehade *et al.*, 2018). Bio-stimulants are an attractive alternative to chemical-based fertilizers. During recent years, several international and national projects, namely Bio2Bio, Nosahan, and Sunniva, have been initiated to explore the production of advance bio-stimulants from agriculture waste (Xu and Geelen, 2018). The global market of bio-stimulations is forecasted to reach $2.2 billion by 2018 (Calvo, Nelson, and Kloepper, 2014).

Over the years, numerous environmentally friendly bio-stimulants have been manufactured using agriculture waste such as a protein hydrolysate (PH) synthesized from soybean meal (Jain and Badve, 2022). This soybean meal-derived PH significantly enhanced the survival, germination, and overall growth of fenugreek and wheat plants. A soil application of PH-based bio-stimulant (GHI_16_VHL) substantially mitigated the severe effect of drought stress on *Capsicum annuum* due to increased levels of non-enzymatic antioxidants, catalase activity, higher stomatal density, and enhanced accumulation of non-structural carbohydrates in leaves (Agliassa *et al.*, 2021).

Recently, La Spada *et al.* (2021) prepared a mixture of natural bio-stimulant derived from alfalfa, sugarcane, and seaweed extract and the conventional fungicide imazalil to control the post-harvest rot of orange fruits. The authors found that the application of a mixture of imazalil and natural bio-stimulant at a low dose on orange fruits substantially reduced the severity and rate of infection caused by *Penicillium digitatum* via upregulating the expression of PEROX- and PAL-encoding genes in fruit peels. Abou Chehade *et al.* (2018) reported that natural bio-stimulant from fennel processing residues (FPR) significantly increased the shoot growth, dry matter content, vitamin C content (20% more than the control), total mineral content, citric acid content, and overall yield of tomato plants.

Recently, Bibi *et al.* (2022) reported the production of bio-organic fertilizer by solid-state fermentation of agro-waste by *Burkholderia cenocepacia*. This organic fertilizer enhanced the germination index, seed vigor index, chlorophyll content, protein content, relative water content, and other growth parameters of maize. Ngan and Riddech (2021) demonstrated that spent mushroom waste (SMW) substantially improves the plant growth, chlorophyll content, and soil properties including organic matter content, soil enzyme level, soil PGPRs, and NPK level; therefore, SMW could potentially be used as a cheap alternative source of bio-fertilizer.

Recently, Jeguirim *et al.* (2020) developed an environment-friendly and economically viable strategy for the conversion of olive mill wastewater into bio-fertilizer (biochar). El-Bassi *et al.* (2021) demonstrated that the olive mill waste-derived biochar (OMWB) significantly increased the phosphatase, urease, protease, and dehydrogenase activity in soil. Moreover, it also accentuated the growth of tomato seedlings. Therefore, OMWB has immense potential as a bio-fertilizer in the agriculture sector.

Farid *et al.* (2022) found that the co-compost biochar derived from sugarcane bagasse and rice straw substantially improves the carbon balance, soil properties, and zucchini growth in sandy arid soils. Ismaiel, Ahmed, and Sobhy (2019) reported that sugarcane bagasse and rice straw waste enhanced the growth of *Triticum aestivum* via cellulose production by *Aspergillus niger*.

16.2.3 Bioprotein

The products derived from bioconversion of agricultural waste are reported to contain a high amount of bioprotein and nutrients (Sadh, Duhan, and Duhan, 2018). Recently, Nuradibah et al. (2020) achieved substantial production of bioprotein (0.381 mg/ml) using spent *Phanerochaete chrysosporium* (ATCC 24725) substrate (60% substrate concentration and 15% (w/v) inoculum size). Fruit waste substrate such as pineapple, mango, papaya, and banana was used for the production of SCP using baker yeast as an alternative food supplement for human beings and animals (Dunuweera, Nikagolla, and Ranganathan, 2021). Oil palm fronds were used for the fabrication of SCP using *Aspergillus terreus* strain (UniMAP AA-1) by solid-state fermentation as an alternative substitute of conventional protein (Rahman, Ariffin, and Abdul Rahim, 2021). Recently, Ma *et al.*, (2018) extracted proteins from cottonseed meal through cold-pressed solvent, hot-pressed solvent, and subcritical fluid. The authors suggested that the proteins derived from cottonseed meal have remarkable prospects as functional ingredients in the food industry. Mondal *et al.* (2012) reported significant production of SCP using cucumber peels and *Saccharomyces cerevisiae* through submerged fermentation process.

Recently, Mahan *et al.* (2018) demonstrated that *Rhodococcus opacus* strains have the ability to produce single-cell proteins (SCPs) using agricultural waste as a cheap carbon source. Mensah and Twumasi (2017) reported that pineapple waste could serve as a potential source for production of economically valuable SCPs using *Saccharomyces cerevisiae*. Acid-hydrolyzed *Carica* papaya waste was used as a carbon source for enhanced production of SCPs and polyhydroxyalkanoates (Umesh *et al.*, 2017). Rao, Varma, and Deshmukh (2010) reported the increased production of SCPs, xylanase, and amino acid by *Penicillium janthinellum* using ammonium sulfate as a nitrogen source and bagasse hemicellulose as a carbon source.

16.2.4 Bio-composites

Bio-composites derived from agriculture waste have generated prodigious interest in several industries including food packaging, automotive, agricultural, and biomedical industry (Nida, Moses, and Anandharamakrishnan, 2020; Dungani *et al.*, 2017). Recently, Imgharn et al. (2021) reported the synthesis of polyaniline-based walnut and almond shell bio-composites through in situ chemical polymerization method. The authors found that the bio-composites were highly effective in removal of Orange G dye from textile industrial effluents using an adsorption process. Perumal *et al.* (2022) extracted cellulose nanocrystals from areca nut husk fibers and reinforced them in chitosan and polyvinyl alcohol films for the preparation of nano-bio-composite (NBC) film. This NBC film exerted strong antimicrobial activity against post-harvest pathogenic fungi and foodborne pathogenic bacteria; therefore, it might be suitable for food packaging applications.

A novel bio-composite-based material was developed by reinforcement of pectin with different amounts of lignocellulose extracted from citrus pomace waste for fabricating biodegradable bio-composite mulching film for crop protection (Xie *et al.*, 2022). The bio-composites derived from renewable rice husk and biodegradable polylactic acid are used as cheap eco-friendly material for three-dimensional printing applications (Wu and Tsou, 2019). Cork, vine pruning residues, prickly pear, and rice husk waste were bound with water-based acrylic resin to form a sustainable bio-composite material for the production of eco-friendly noise-controlling ceiling tiles or panels (Maderuelo-Sanz *et al.*, 2022). Bhatti *et al.* (2018) have fabricated a bio-composite material from mango stone waste for treating wastewater by removal of phosphate ions through absorption process.

Several researchers have reported that the bio-nanocomposite derived from agricultural waste has tremendous potential in biomedical applications, in particular, tissue engineering (Duolikun, Lai, and Bin Johan, 2021). Recently, Skrzypczak *et al.* (2021) fabricated bio-composite material from agriculture waste to develop a controlled-release fertilizer. This bio-based material showed high sorption capacity of copper ions and slows down the release of nutrients.

16.2.5 Biodegradable plastic

Biodegradable plastic represents 1% of 0.3 billion tons of annual plastic production (Chan *et al.*, 2021). Recently, Reshmy *et al.* (2021) successfully developed an environment-friendly and cost-effective nano-cellulosic-based biodegradable plastic from different plasticizers, *Boswellia serrata* (as filler), and jackfruit peel cellulose. Shanmathy, Mohanta, and Thirugnanam (2021) reported the production of environmentally benign biodegradable bioplastic films by reinforcement of bentonite with taro starch. This biodegradable bioplastic is more resistant to acid and salt and may serve as an effective alternative to synthetic plastic. Recently, sugarcane bagasse was used for the fabrication of carboxymethyl cellulose-based bioplastic material for food packaging applications (Yaradoddi *et al.*, 2020). Rishi *et al.* (2020) demonstrated the production of low-cost biodegradable plastic from pullulan developed through fermentation of hydrolyzed kitchen waste by *Aureobasidium pullulans* (MTCC 2013). Iriani *et al.* (2019) reported the fabrication of bioplastic bags by reinforcement of nanocellulose from palm empty fruit bunch and rice straw. These bioplastic bags have tremendous potential in production of fresh fruit packaging material. Agriculture waste such as banana pseudo-stem was used for the fabrication of nanocellulose-based biodegradable plastic using plasticizers with graphene oxide and nano-clay as fillers (Faradilla *et al.*, 2018).

Mostafa *et al.* (2018) fabricated cellulose acetate fibers-based biodegradable plastic from cotton linters and flax fibers. This biodegradable plastic is more resistant to acid compared to polystyrene and polypropylene; therefore, it has tremendous potential in the pharmaceutical and food industries. Getachew and Woldesenbet (2016) reported the cost-effective production of biodegradable plastic from polyhyroxybutyrate accumulating *Bacillus* sp. using pretreated banana peel, sugarcane bagasse, teff straw, and corn cob waste as carbon source. Agriculture waste including sugarcane bagasse and cocoa pod husk cellulose was used for the development of biodegradable plastic films for food packaging applications (Azmin, Hayat, and Nor, 2020).

16.3 Achieving SDGs through agro-waste innovations

16.3.1 Clean water

During recent years, the increased discharge of chemicals and industrial effluents in aquatic systems has led to severe contamination and drastic reduction in the quality of freshwater (Ma'arfi *et al.*, 2021). Presently, over 1 billion population lack basic access to freshwater (Ma'arfi *et al.*, 2021). A recent review by Kumar *et al.* (2019) reported that the average content of heavy metals including As, Mn, Cr, Cd, Co, and Ni in surface water exceeded the permissible limits suggested by USEPA and WHO. Contaminated water poses a great threat to the ecological environment and human health. Conventional biological water treatment methods are ineffective and expensive. Recently, advance biological material derived from agriculture waste has received immense interest for the treatment of contaminated water (Ugwu and Agunwamba, 2020). Agricultural waste such as banana peel was used as a cost-effective adsorbent for removing methylene blue from batik textile wastewater effluents (Abu Bakar *et al.*, 2019). The maximum removal of methylene blue from wastewater effluents was found to be 86.22%. Rice husk was used as a low-cost adsorbent for the removal of heavy metals such as Ni, Fe, and Pb (20−60 mg/L) from the contaminated water discharged from electroplating industries (Hegazi, 2013).

Recently, Binh, Nguyen, and Kajitvichyanukul (2022) successfully developed a hydrochloric acid-modified corn cob bio-waste sorbent via pyrolysis for adsorption of atrazine from contaminated water. The bio-waste sorbent exhibited maximum adsorption capacity in the range of 11.31 to 19.58 mg/g. The toxic hydrogen sulfide was successfully removed from the petroleum industry wastewater using activated carbon derived from palm kernel shells (Habeeb *et al.*, 2020).

Recently, Baby, Saifullah, and Hussein (2019) successfully developed a cost-effective method for removal of heavy metals (Cr, Pb, Cd, Zn) from contaminated water using palm oil kernel shells as a green adsorbent. Rhodamine B dye was effectively removed from aqueous solution by activated carbon produced from ortho-phosphoric acid-modified locust bean husk. The maximum adsorption capacity was estimated to be 1111.1 mg/g (Bello *et al.*, 2019). The water contaminated with cationic dye was treated using nano-porous activated carbon fabricated from almond and walnut shells. The maximum adsorption capacity of nano-porous carbon produced from walnut shells was found to be 114 mg/g (Teimouri, Salem, and Salem, 2019).

16.3.2 Affordable and clean energy

Presently, the primary energy sources (petroleum, natural gas, and coal) are rapidly decreasing at an alarming rate due to unchecked increase in energy demand by a rapidly expanding population (Kaur and Sarao, 2021; Gupta and Mondal, 2019). In the near future, the world is facing a huge risk of energy crisis (Kaur and Sarao, 2021). Therefore, there is an urgent need for a green and affordable source of energy. Among various resources, agriculture waste is a cost-effective, sustainable, and green alternative source of energy (Kaur and Sarao, 2021; Gupta and Mondal, 2019).

The production of bioenergy from agriculture waste generally depends on the biomass properties (Gupta and Mondal, 2019). Different technologies such as pyrolysis, torrefaction, anaerobic digestion, incineration, pyrolysis-combustion, and liquefaction are widely used for the conversion of agriculture waste to bioenergy (Alhazmi and Loy, 2021). Hamawand et al. (2016) reported that 24.8 PJ of bioenergy can be potentially generated from burning cotton stalks. The potential revenue from this bioprocess can be 0.1 billion dollars. The rice straw was gradually pyrolyzed at different temperatures for the sustainable production of biochar, which was subsequently utilized for the generation of electricity (Kumar Sakhiya *et al.*, 2021).

Recently, Bhat *et al.* (2020) prepared cost-effective porous nano-carbon-based supercapacitors from agricultural waste using a pyrolysis method at different temperatures. The supercapacitor showed 97.8% coulombic efficiency, 93% capacitance retention at the end of 10,000 cycles, 32.6 Wh/kg specific energy, and specific capacitance of 119.2 F/g at 0.1 A/g. Zou *et al.* (2018) also developed a high-performance supercapacitor from nitrogen-doped carbon derived from activation of bagasse using urea and potassium hydroxide. The supercapacitor exhibited high energy density (39.1 Wh/kg), excellent long-term cyclic stability (95.0% after 10,000 cycles), high specific capacitance (350.8 F/g at 0.1 A/g in acidic electrolytes), and superior rate capability.

The combustion of rice straw can potentially generate 142 GWh/year of energy that is sufficient to cater 30% of the energy demand of the local Novara town (Bressan *et al.*, 2022). The anaerobic digestion of banana waste has high potential for the sustainable production of affordable and clean energy in Uganda (Gumisiriza *et al.*, 2017). Vakalis *et al.* (2019) proposed the concept of a renewable battery through conversion of agricultural waste to bio-coal via frictional pyrolysis. The 24.3 million tons of agriculture waste were used as feedstock for the generation of 6.5 billion meter cube of biogas and 62,808 $\times$ 106 kWh/year of bio-power in Iran (Safieddin Ardebili, 2020).

16.4 Assessment of the bioenergy potential of agriculture waste

The extensive agriculture production after the Green Revolution presented the agriculture sector as a key driver of economic change throughout the world (Duque-Acevedo *et al.*, 2020). A large amount of livestock manure generated during agricultural systems addresses the circular economy technique utilizing animal waste for producing biogas, bio-fertilizer, and biofuel creating a sustainable impact on food security and environmental aspects (Xu *et al.*, 2018). It also has a major impact on the ever-expanding energy demands of various industries. However, waste management, in terms of the ecological cycle, converts the best utilization of agro-waste into useful bioenergy without releasing toxic residuals released into the air, water, and soil (Vega-Quezada, Blanco, and Romero, 2017). Moreover, the circular approach controls the flow of microplastics into aquatic bodies and landfills (Bluemling and Wang, 2018). Therefore, a systemic study on agricultural applications ranging from raw materials and processing to final product/activity with undesirable emissions should be evaluated. Accordingly, the life cycle of some crops may be enhanced since they can be used to obtain co- and byproducts that, in turn, may lead to bioplastics that could be reused again in the first stages of their life cycle (e.g., as water suppliers or for nutrient delivery to enhance crop growth) (Ramos-Suárez *et al.*, 2019). Furthermore, the identification of waste management challenges and their interconnection should be discussed in framing sustainable policies on agro-waste management. The multidimensional analysis will facilitate the inadequacies in agricultural residue converting technologies for environmental security. Thus, conversion of the agro-waste is an intensive process based on a zero-waste policy, where natural and sustainable products like fertilizers, energy, materials, molecules, and other value-added products are generated without adding pressure on land, existing biodiversity, and food security. Considering the paramount importance of the circular economy approach, certain initiatives to achieve circular agriculture strategy by agricultural operations were considered for achieving SDGs and environmental benefits on a larger scale by governments for agricultural waste management (Elsheekh *et al.*, 2021).

Different agricultural waste utilization strategies and their environmental benefits toward achieving Sustainable Development Goals (SDGs) and meeting energy demands of different industries are shown in Table 16.1. Briquettes from crop residues offer cleaner cooking alternatives, addressing SDGs 1, 2, 3, 7, and 13 in Mali. Microalgae biofuel production in Ecuador supports SDGs 7, 9, 13, 14, and 15. Cellulosic ethanol production from sugarcane and banana waste in Maharashtra, India, contributes to SDGs 7, 9, 13, 12, and 15. Biogas generation from livestock manure in the Canary Islands and Zhejiang province, China, advances SDGs 7, 9, 11, 13, and 15. Finally, bioelectricity generation from crop residues in Cameroon aids in achieving SDGs 7 and 13. These strategies collectively promote renewable energy access to various industries, climate action, and sustainable waste management practices.

TABLE 16.1 Bioenergy potential of various crop residues for circular economy, meeting industrial demands, and achievement of SDGs.

Circular agriculture strategy	Agricultural operations	Environmental benefits and achieving SDGs	Country	Reference
Briquettes (Cooking fuel)	Briquettes from agricultural residues of different crop wastes such as millet straw, sorghum straw, mango, and cotton stalks used for cooking purposes.	Transitioning to clean cooking with briquettes curbs firewood and LPG usage, while locally sourced biofuels are environmentally neutral. Briquettes from agricultural residues address multiple SDGs: SDG 1: No Poverty—They provide a cheaper fuel source, reducing household fuel costs. SDG 2: Zero Hunger—Utilizing residues diverts waste, enhancing food security. SDG 3: Good Health and Well-being—By reducing indoor air pollution from traditional fuels, they improve respiratory health. SDG 7: Affordable and Clean Energy—Briquettes offer a cleaner alternative, ensuring access to sustainable energy. SDG 13: Climate Action—Using residues for briquettes reduces emissions, curbing deforestation and land degradation.	Mali	(Segura-Rodríguez and Bhandari, 2024)
Biodiesel	Replacement of traditional energy crops with microalgae farming preferably closed cultivation Microalgae grown in a laminar photobioreactor is superior to palm oil. Also, microalgae put less pressure on agricultural land and present a better carbon balance.	Microalgae offer environmental benefits by recycling carbon dioxide in production, reducing land pressure, and generating revenue through glycerin production. Additionally, algal residue serves as feed, completing a sustainable cycle. Leveraging microalgae offers a pathway to sustainable energy, fostering environmental and social progress. SDG 7: Affordable and Clean Energy—Microalgae provide sustainable biofuels, advancing clean energy access. SDG 9: Industry, Innovation, and Infrastructure—Microalgae farming fosters innovation and infrastructure development. SDG 13: Climate Action—Microalgae absorb carbon dioxide, aiding in greenhouse gas reduction and climate resilience. SDG 14: Life Below Water—Closed cultivation prevents water pollution and protects marine ecosystems. SDG 15: Life on Land—Microalgae farming reduces land pressure, promoting biodiversity and conservation.	Ecuador, Latin America	(Vega-Quezada, Blanco and Romero, 2017)
Cellulosic Ethanol (Biofuel)	Sugarcane and banana wastes are suitable for biofuel production as the cellulose content (44.78% and 42.7% for sugarcane and banana, respectively). Most of the agro-wastes are disposed of either by burning or by dumping them in fields causing environmental pollution. Cellulosic materials are particularly attractive as feedstock for biofuel production because of their relatively low cost, great abundance, sustainable supply through technological interventions.	Cellulosic ethanol production from agricultural waste reduces reliance on fossil fuels, mitigating greenhouse gas emissions. It also promotes waste valorization, contributing to a more sustainable agricultural system. Cellulosic ethanol production supports: SDG 7: Affordable and Clean Energy—Offers renewable fuel options. SDG 9: Industry, Innovation, and Infrastructure—Drives technological advancements. SDG 13: Climate Action—Reduces greenhouse gas emissions. SDG 12: Responsible Consumption and Production—Utilizes agricultural waste efficiently. SDG 15: Life on Land—Lessens pressure on agricultural land, aiding biodiversity.	Maharashtra, India	(Gabhane *et al.*, 2016)

Continued

TABLE 16.1 Bioenergy potential of various crop residues for circular economy, meeting industrial demands, and achievement of SDGs.—cont'd

Circular agriculture strategy	Agricultural operations	Environmental benefits and achieving SDGs	Country	Reference
Biogas	Biogas from the anaerobic digestion of animal manure and agriculture waste to produce renewable energy. Economically viable small-scale biogas plants, generating 185 kW of electricity using livestock manure as substrate Cooperation between farmers for energy self-sufficiency	Using biogas from agricultural waste reduces methane emissions and provides renewable energy, benefiting both the environment and waste management practices. Biogas supports several Sustainable Development Goals (SDGs): SDG 7: Affordable and Clean Energy—Provides a renewable and sustainable energy source. SDG 9: Industry, Innovation, and Infrastructure—Encourages innovation in waste management technologies. SDG 11: Sustainable Cities and Communities—Improves urban waste management and reduces pollution. SDG 13: Climate Action—Mitigates greenhouse gas emissions and contributes to climate resilience. SDG 15: Life on Land—Promotes sustainable land use practices and soil health by utilizing agricultural waste.	Canary Islands Zhejiang province, China	(Ramos-Suárez *et al.*, 2019)
Bioelectricity	Bioelectricity potential from crop residues represented the highest energy potential are plantains, palm oil, maize, sorghum, and cassava at 183 PJ/y, 80 PJ/y, 71 PJ/y, 37 PJ/y, and 32 PJ/y, respectively.	Bioelectricity from agricultural waste offers environmental benefits by reducing methane emissions and providing a renewable energy source, contributing to sustainable waste management and mitigating climate change. Achieving SDGs using bioelectricity from agricultural waste: SDG 7: Affordable and Clean Energy—Provides renewable energy access, fostering sustainability. SDG 13: Climate Action—Reduces greenhouse gas emissions, mitigating climate change effects and promoting environmental resilience.	Cameroon, Africa	(Tanyi and Adaramola, 2023)

16.5 Conclusion

In conclusion, the industrial application of agricultural waste to create value-added products is a transformative approach that fosters a shift from a traditional linear economy to a more sustainable, circular one. Despite the varying interpretations of circular economy principles among organizations and researchers, a unified understanding is crucial for effective implementation. Addressing these inconsistencies will enable stakeholders to fully harness the potential of agricultural waste. This chapter highlights how the valorization of agricultural residues such as hemicellulose, lignocellulose, and lignin, through technological advancements, can lead to the production of biodegradable plastics, bio-composites, bio-stimulants, bio-fertilizers, and biomedical materials. These innovations not only replace conventional materials but also contribute to environmental sustainability by reducing waste and improving resource efficiency.

Moreover, agricultural waste is repurposed in diverse industrial sectors including environmental remediation, wastewater treatment, and green energy production, which supports several Sustainable Development Goals (SDGs). By prioritizing the reuse of agricultural waste in bioenergy production, we can enhance energy security, reduce environmental impact, and lower production costs. The successful integration of agricultural waste into sustainable industrial practices promotes economic and environmental sustainability, paving the way for innovative and eco-friendly industrial solutions.

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Chapter 17

Nanotechnology and agro-industrial wastes as a sustainable and future approach in agricultural applications

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Chapter Outline

17.1. Introduction 267
17.2. Nanotechnology applied in agriculture 268
17.3. Strategies for nanoparticles production 270
17.4. Agricultural wastes as a source of materials for NPs 271
17.5. Potentiality of nanoparticles in agriculture 272
17.6. Mechanism of action of the nanoparticles 274
17.7. Challenges 275
17.8. Conclusion and future perspectives 275
Acknowledgments 276
References 276

17.1 Introduction

The agricultural sector benefits from science and technology, bringing new ideas and solutions to reduce and/or solve problems. In this context, nanotechnology emerges because it is a promising approach using efficient nanoformulations for sustainable agriculture, with crop improvement and higher productivity (Neme *et al.*, 2021; Mittal *et al.*, 2020). The application of nanotechnology in agriculture aims to reduce nutrient losses to increase yields and reduce the amounts of products applied for plant protection (Usman *et al.*, 2020). Nanotechnology also can contribute to monitoring plant growth, ensuring improved food quality, and increasing global food production (Jampílek and Králová, 2017). Nanomaterials present potential in agriculture in seed coating, pest and disease control, and controlled release of nano-fertilizers and nano-pesticides. They provide controlled release of chemicals for cultivation at the right time and place, with specific

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concentrations, thus reducing excess use. Moreover, nanomaterials can be produced from wastes, offering agricultural sustainability and a higher cost-benefit ratio (Moreira *et al.*, 2022a).

Nanotechnology can offer advantages to pesticides, such as reducing toxicity, improving shelf life, and increasing the solubility of poorly water-soluble pesticides (Worrall *et al.*, 2018; Chand Mali, Raj, and Trivedi, 2020). Nanotechnology also increases the chemical stability and bioavailability of the pesticide, improves the absorption of the compound by the soil, and reduces the photodecomposition of the components present in the agricultural defender (Jampílek and Králová, 2017). Nano-pesticides assist in the slow and continuous supply of nutrients and agricultural chemicals in a controlled amount to the plants (Duhan *et al.*, 2017). Nano-fertilizers provide nutrients to plants and can enhance the effect of fertilizers even when applied in smaller amounts. In addition, nano-fertilizers can reduce the loss of nutrients, mainly phosphorus and nitrogen, offering a gradual and controlled release of nutrients to the destination site. With this, using nano-fertilizers helps to avoid contamination of water bodies and the environment (Mittal *et al.*, 2020).

The nanomaterials are proposed for agriculture to reduce the spraying of chemicals by delivering them in a gradual and controlled manner (Neme *et al.*, 2021). In this context, nanoparticles (NPs) have the potential to be incorporated into a variety of products in the agriculture and food sectors, due to their unique and emerging properties (Mittal *et al.*, 2020; Jeevanandam *et al.*, 2018). In addition to the controlled release capacity of active compounds, other characteristics include biocompatibility, protection of active compounds from environmental factors, high solubility, and efficient delivery of nutrients (Acharya and Pal, 2020). These nanostructures can be added directly to cultures or as a delivery system for active nutrients (Bala, Kumar Bansal, and Fatima, 2023).

Studies show that NPs provide improved resistance to insects and phytopathogens (Zhang *et al.*, 2023; Kang *et al.*, 2022), increased antioxidant activity and reduced oxidative stress (Rady *et al.*, 2023), and absorbed toxic compounds such as metals (Ogunkunle *et al.*, 2020). In addition, NPs act in the bioremediation of soils contaminated with polycyclic aromatic hydrocarbons (Liu *et al.*, 2023) and pest and host pathogens control (Neme *et al.*, 2021).

In this sense, this chapter addresses the use of NPs and wastes (agricultural and industrial) for developing nano-pesticides and nano-fertilizers to contribute to sustainable agriculture. This work brings other aspects, such as NP synthesis processes and mechanisms of action, and the main challenges of nanotechnology in the agricultural sector.

17.2 Nanotechnology applied in agriculture

The application of nanotechnology in agriculture is an interesting approach since it can increase crop productivity and promote the sustainable management of food and agricultural waste (Acharya and Pal, 2020; Adebisi *et al.*, 2021). Sustainability and the circular economy are topics frequently discussed in the scientific and industrial scenario, with potential applications in the agricultural sector (Preethi *et al.*, 2024; Velasco-Muñoz *et al.*, 2022). Nanotechnology can contribute to the application of these concepts in agriculture, for example, by promoting the sustainable disposal of waste generated in agricultural practices. Metallic NPs are nanomaterials that can accelerate the process of enzymatic breakdown of complex organic compounds, facilitating composting and anaerobic digestion (Shah *et al.*, 2024; Nagaraja, Arunpandian, and Tae Hwan, 2024; Khodabandeh, Nagy, and Török, 2023). Some portions of agricultural waste, such as cellulose, can also be directed to develop nanomaterials such as nanofibers or NPs (Riseh *et al.*, 2024). These materials are considered excellent adsorbents due to their high surface area and porosity and can act to remove pollutants from wastewater (Manikandan *et al.*, 2023).

Nanotechnology can also contribute to reducing the impacts that chemical agricultural defenders have on soil and water. NPs can act as nano-pesticides, nano-herbicides, and nano-fertilizers (Bala *et al.*, 2023). These nanostructures can be added directly to crops or used as an active nutrient delivery system (Figure 17.1).

17.2.1 Pesticides

Agriculture is a sector of great economic relevance, as it is responsible for obtaining agricultural products for human and animal consumption (Malhotra, 2016). In this context, the growth of the world population brought the need to develop efficient agricultural techniques to meet the food demand (Fukase and Martin, 2020). Because of this, applying pesticides to crops has become a practice resulting from all stages of the food production process (Galani *et al.*, 2021). Agricultural defensives or pesticides are chemical/biological compounds used to control pests or undesirable microorganisms in plantations, intending to improve the quality and productivity of crops (Zowada *et al.*, 2020). However, these substances represent a danger to the environment and public health, making it necessary to study new alternatives for controlling pests of food crops and protecting plants (Acharya and Pal, 2020). Pesticides can be presented as fungicides, herbicides, insecticides, nematicides, and acaricides (Maino *et al.*, 2023; Adenubi *et al.*, 2018).

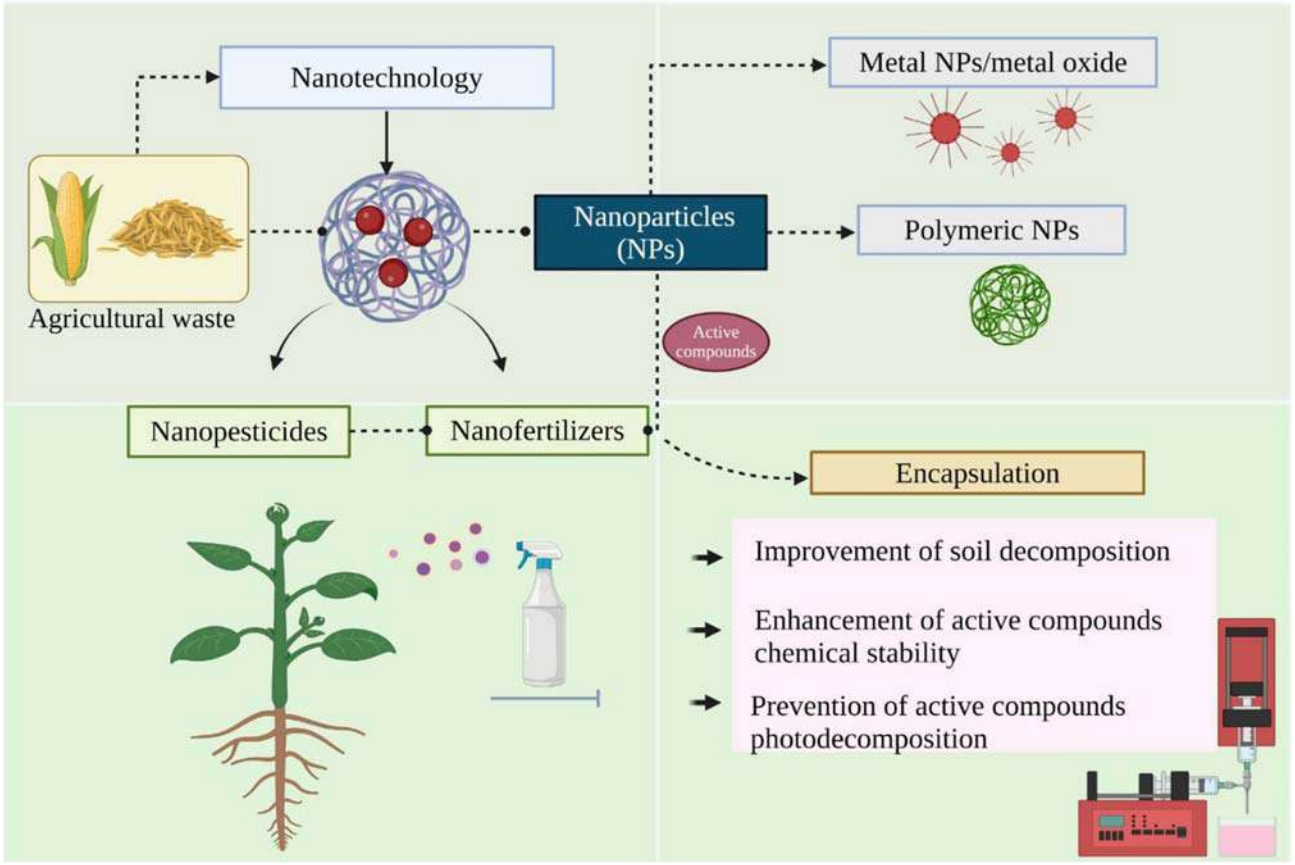


FIGURE 17.1 **Application system of nanoparticles (NPs) in agriculture as nano-pesticides or nano-fertilizers.**

The main disadvantages of pesticides are related to environmental problems, as about 90% of these substances are dissipated into the atmosphere and do not biodegrade in the environment (Acharya and Pal, 2020). In addition, herbicides have a limitation since they do not act on different parts of the plant. As a result, there is less efficiency in the treatment of pests. Therefore, it is necessary to apply herbicides with different mechanisms of action, as some are efficient when applied directly to the leaves and others to the roots (Acharya and Pal, 2020; Shang *et al.*, 2019).

The degradation of the active compound by environmental factors such as light, temperature, salinity, and physico-chemical properties of the soil, such as texture and organic matter content, can influence the efficiency of pesticide activity (Acharya and Pal, 2020; Jeong and Forster, 2003). In this way, nanotechnology has emerged as an alternative to increasing the chemical stability and bioavailability of the pesticide, improving the absorption of the compound by the soil, and reducing the photodecomposition of the components present in the agricultural defender. The development of nanocarriers allows the controlled release of pesticides (Jampílek and Králová, 2017). Because of this, nanoencapsulation technologies have been widely studied to improve plant protection (Singh and Gurjar, 2022).

NPs are considered promising for increasing the efficiency of agricultural processes and may be included in pesticide formulations and sprayed directly on cultivars. In addition, these nanomaterials can act as a vehicle for transporting agricultural pesticides, promoting the controlled release of these compounds into the soil (An *et al.*, 2022; Bala, Kumar Bansal, and Fatima, 2023; Worrall *et al.*, 2018). Nanomaterials such as metallic and polymeric NPs have been extensively studied for application in agriculture (Mishra *et al.*, 2017). Polymeric NPs have great potential for replacing conventional pesticides. These nanostructures can be developed with natural and biodegradable polymers. Furthermore, using these nanomaterials as agrochemical carriers has the advantages of biocompatibility, protection of active compounds from environmental factors, high solubility, and controlled release of these compounds (Acharya and Pal, 2020). Studies involving the application of nano-pesticides in agriculture have been consolidating the effectiveness of these nanomaterials in pest control (Zheng *et al.*, 2022; Pascoli *et al.*, 2019). Using NPs as pesticide carriers has been the focus of studies for improving the agricultural area (Pan *et al.*, 2023). However, for greater commercial interest in pesticides incorporated into NPs, the toxicity of these products to human health should be better investigated (Takeshita *et al.*, 2023).

17.2.2 Fertilizers

Supplying macronutrients and micronutrients is necessary for the healthy growth of the product and efficiency in plantations. Chemical fertilizers are sources mainly of nitrogen (N), phosphorus (P), and potassium (K), which are crucial for the development of agricultural products (Arora *et al.*, 2022; Tarafder *et al.*, 2020). However, applying fertilizers in high concentrations (generally between 100 and 650 kg/ha) in plantations can cause numerous environmental problems (FAO, 2009). Some of the macronutrients, such as N, P, and K, are lost by 40 to 70%, 80 to 90%, and 50 to 90%, respectively, contributing, in the long term, to soil and water contamination (Chen and Wei, 2018; Feregrino-Perez *et al.*, 2018; Liu and Lal, 2015; Solanki *et al.*, 2015). Moreover, the need to obtain greater productivity with the uncontrolled use of these substances can affect soil fertility and the quality of the cultivated product. In this way, it is necessary to develop new alternatives to promote the slow and controlled release of fertilizers (Feregrino-Perez *et al.*, 2018).

Biologically based fertilizers (plant, animal, or microbial origin) have emerged as likely substitutes for synthetic products applied in the agricultural sector, as they improve nutrient replenishment and soil quality (Bhardwaj *et al.*, 2014). Although they have several positive aspects, the application of bio-fertilizers is still not chosen by farmers, as they should produce the substance at the application site, as long-distance transport can be costly (Chittora *et al.*, 2020).

Combining agriculture with nanotechnology is a promising alternative to increase crop yields. In this sense, nano-fertilizers have emerged to replace traditional chemical fertilizers and make the process more efficient (Kanjana, 2017; Derosa *et al.*, 2010). Release systems are produced by immobilizing nutrients in nanomaterials by three methods: (a) encapsulation in nanoporous structures, (b) by coating in polymeric films, or (c) by delivery in the form of NPs (Davari, Bayat Kazazi, and Akbarzadeh Pivehzhani, 2017; Rai, Acharya, and Dey, 2012). The reduced size of nano-fertilizers (between 1 and 100 nm) favors the efficiency of nutrient delivery, as it can access the surface of plants and transport channels (Mastronardi *et al.*, 2015; Zhou, Liu, and Liu, 2014).

The mechanism of slow and controlled release of nutrients is the main characteristic of nano-fertilizers, as it acts according to the nutritional needs of plants and environmental conditions (Arora *et al.*, 2022). Thus, the cultivars are neither in deficit nor over nutrients, which can influence the growth process (Acharya and Pal, 2020). In addition, nanoencapsulated fertilizers reduce nutrient loss to soil and water bodies, improve soil quality, and protect compounds against volatilization, heat, and UV damage (Arora *et al.*, 2022).

Nano-fertilizers have been fitting into the concept of sustainable technology. Applications of low concentrations on plants improve crop yields and reduce environmental damage (Usman *et al.*, 2020). Nanoformulations may also have antimicrobial capacity, helping to control diseases, being effective against pests, and favoring the biosynthesis of secondary metabolites (Ghorbanpour and Hadian, 2015; Syu *et al.*, 2014). On the other hand, regulatory requirements and risks of these nanoproducts to human health in the long term are not yet known (Gómez Martín *et al.*, 2020). Furthermore, applying high concentrations of these nanomaterials to plants' non-target parts can cause cellular damage and genetic alterations (Jampílek and Králová, 2017). Research areas need to estimate the effects of fertilizers on human health and the environment, as it is a promising alternative to increase crop productivity sustainably.

17.3 Strategies for nanoparticles production

The production of NPs from fertilizers and pesticides has been the subject of research around the world, intending to find innovative solutions and approaches that demand high efficiency, low energy and cost, and less negative impact on the environment (NDABA *et al.*, 2022; Fatima, Hashim, and Anees, 2021; Maghsoodi, Ghodszad, and Asgari Lajayer, 2020). Several elements and/or compounds can be used to form NPs for developing nano-fertilizer/nano-pesticide formulations. These nanostructures can be synthesized using physical, chemical, or biological methods (Zulfiqar *et al.*, 2019; Vijayaraghavan and Ashokkumar, 2017). According to NDABA *et al.* (2022), biological synthesis is preferable because it uses fewer chemicals and has fewer adverse effects. This process uses bacteria, fungi, plant extracts, and enzymes. The physical process is based on evaporation, condensation, laser ablation, ball milling, and melt mixing. The chemical method involves sol-gel, hydrothermal, polyol, and steam chemical synthesis processes (Neme *et al.*, 2021).

Biological, chemical, and physical pretreatments or a combination of these processes are needed to transform agricultural waste into simpler structures. The composition of the waste material and the desired NPs should be considered for the selection of the pretreatment. In addition, pretreatments can help to remove contaminants that may affect the development of NPs. Pretreatments are a prerequisite for the subsequent synthesis of NPs (Flores-Contreras *et al.*, 2024; Judith and Vasudevan, 2022). The synthesis of NPs can involve, generally, two approaches: (a) top-down and (b) bottom-up (Figure 17.2). The top-down approach uses physical methods and techniques such as milling, laser/thermal ablation, and sputtering to decompose the material into nanosized particles (Neme *et al.*, 2021; Gudkov *et al.*, 2020). Bottom-up

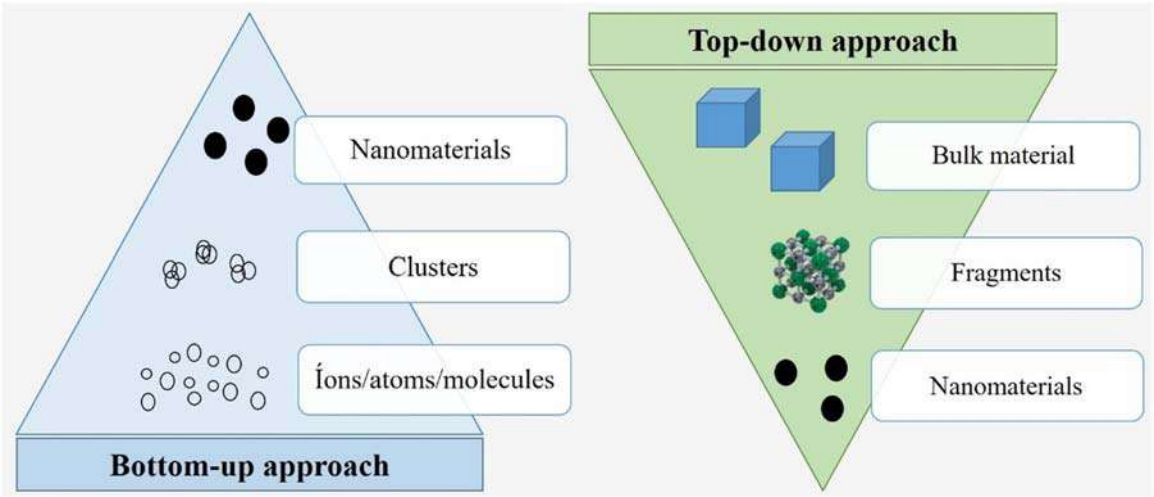


FIGURE 17.2 **Bottom-up and top-down approaches in nanoparticle synthesis.**

targeting involves the production of NPs using chemical and biological methods from much smaller substances (atoms and molecules) (NDABA *et al.*, 2022; Neme *et al.*, 2021). These smaller molecules can grow into large particles in the nanoscale range. First, the molecules are subjected to evaporation and controlled condensation (Neme *et al.*, 2021). Most NPs obtained by bottom-up process present a solid nature, being first applied mechanical methods (high-energy ball milling, cutting, etching, grinding, machining, polishing) or lithography approaches such as electron-beam and photolithography (NDABA *et al.*, 2022; Neme *et al.*, 2021).

The NPs synthesized under the bottom-up approach are more homogeneous when compared to the top-down approach. The bottom-up process allows for better particle size control and reduction of impurities in the final product (Zulfiqar *et al.*, 2019; Pradhan and Mailapalli, 2017). Moreover, it should be noted that it is important to control possible contaminants resulting from impurities on the surface of the NPs since they can compromise their physicochemical properties and biological activity (NDABA *et al.*, 2022; Saratale *et al.*, 2018).

The physical and chemical properties of the NPs produced vary with the nature (organic/inorganic) and the mode of synthesis, which direct their functionality and efficiency for application in agriculture (NDABA *et al.*, 2022; Neme *et al.*, 2021). Different techniques, such as X-ray diffraction, X-ray photoelectron spectroscopy, and electron microscopy, have been widely used in identifying the nanomaterials' properties (Neme *et al.*, 2021; Khan, Saeed, and Khan, 2019). Thus, depending on the application in agriculture, it becomes essential to analyze the size, surface area, charge, and surface reactivity of the obtained NPs (Neme *et al.*, 2021). According to the study by Reches *et al.* (2018), the smaller the size of the NPs (Al_2O_3, Fe_2O_3, SiO_2, TiO_2), the greater the response of their reactivity. In this context, Oliver-Meseguer *et al.* (2018) observed a positive relationship between surface area, pore size, and chemical reactivity of gold (Au) NPs. The authors reported that the NPs produced showed high reactivity to less active molecules through electron density transfer.

Among the methods of producing NPs for fertilizers/pesticides, the approach via chemical synthesis was the most used (NDABA *et al.*, 2022). However, these methods require using harmful chemical substances with high cytotoxicity, carcinogenicity, and genotoxicity, making them environmentally dangerous (Gahlawat and Choudhury, 2019). Research has advanced in the search for more sustainable, low-cost, and high-commercial methods (Gahlawat and Choudhury, 2019; Zulfiqar *et al.*, 2019). Thus, the synthesis of NPs from biological sources, including algae, fungi, bacteria, and plants, has gained prominence due to the inherent ability of these organisms to absorb and accumulate metal ions (Moreira *et al.*, 2022b; NDABA *et al.*, 2022). According to Salem and Fouda (2021), this biological production of NPs follows a bottom-up approach, where reducing agents of biological origin allow the nucleation of metal ion atoms and the formation of metallic NPs. In this NP production system, advantages can be observed, such as high stability due to the presence of natural buffering and stabilization agents (Phan and Haes, 2019; Sardar and Mazumder, 2018), increased NP yield, and ease of cultivation of organisms to obtain the biological material (NDABA *et al.*, 2022).

17.4 Agricultural wastes as a source of materials for NPs

The agricultural production sector is expanding and is a significant biomass producer, highlighting the importance of managing and transforming agricultural residues into higher-value byproducts (Aminuzzaman *et al.*, 2019). Consequently,

there is growing interest in enhancing the sustainability of processes generating higher-value-added products, which drives the exploration of alternative inputs for NP production. Agricultural wastes such as rice husks, corn stalks, fruit pits, and bagasse are sources with high potential for bioactive compounds and biopolymers such as cellulose, lignin, and hemicellulose. Biopolymers are crucial components for nanomaterials production and thus promote the bioeconomy sector (Ouyang *et al.*, 2023). Agricultural residues present a high potential for sustainably obtaining biopolymers and nanomaterials (Moreira *et al.*, 2022a). A study utilized solid waste from the extraction of bioactive compounds from olive tree leaves to produce nanomaterials. The findings demonstrated through the fractionation of solid waste, various lignocellulosic nanomaterials such as cellulose nanocrystals, cellulose nanofibers, and lignin-containing cellulose nanofibrils could be obtained (Ben Mabrouk, Putaux, and Boufi, 2023). In this way, the valorization of waste and its contribution to the circular economy can be observed, thereby benefiting the development of ecological and economic approaches to producing these nanomaterials (Table 17.1).

Nanomaterials prepared from agricultural residues can be employed in wastewater remediation for removing heavy metals, such as mercury, lead, cadmium, chromium, and arsenic. Additionally, organic pollutants like dyes and pharmaceuticals found primarily in industrial wastewater can be eliminated using NPs (Ouyang *et al.*, 2023). Studies on this theme have directed efforts toward developing NPs (iron oxide, silver) from different wastes (Table 17.1) to remove heavy metals such as lead and chromium from contaminated water and wastewater, considering their harmful effects on human health and the environment. According to the researchers, these nanoadsorbents offered unique properties such as large surface area, regenerability, rapid removal rate, selective binding, scalability, and compatibility, making them highly efficient in adsorbing heavy metal ions from aqueous solutions.

Consequently, studies demonstrate the feasibility of converting agricultural residues into nanomaterials applied as fertilizers, biostimulants, and pesticides. This strategy embodies the principles of a circular economy, enhancing sustainability and fostering innovation in waste management and environmental remediation. Moreover, this approach creates new economic and social opportunities while reducing environmental impacts (Tang *et al.*, 2024).

17.5 Potentiality of nanoparticles in agriculture

The potential of NPs in agriculture is evidenced in several studies (Table 17.2). Zein NPs can act as carriers of the insecticide avermectin, demonstrating that immobilization processes maintain the compound's activity and protect it from external factors (Dai *et al.*, 2022). Selenium NPs acted as a biostimulant, improving plant growth and resistance to insects

TABLE 17.1 Nanoparticles synthesized from agricultural residues and their environmental applications.

Nanoparticles	Material/source	Application	Reference
Starch	Mango seed	Edible coating for fresh produce preservation	(Singh *et al.*, 2024)
Synthesis of silver	Waste of Murcott mandarin peel	Heavy metal removal from metal industrial wastewater	(Aboelghait *et al.*, 2024)
Synthesis of mesoporous silica	Banana peel ash	Adsorption of phenol and methyl orange	(Mohamad *et al.*, 2019)
Bimetallic silver and gold	*Cannabis sativa* and *Vitis vinifera* waste extracts	Effective antimicrobial agents	(Michailidu *et al.*, 2024)
Synthesis of mesoporous silica	Rice husk	Adsorption of methylene blue	(Usgodaarachchi *et al.*, 2021)
Nanocellulose	Wheat straw	Reinforcement for nanocomposites	(Kumar Trivedi, Kumar and Gupta, 2023)
Nanocellulose	Sawn timber industrial wastes	Fabrication of bio-composite membranes	(Zaki *et al.*, 2022)
Ag and Cu	Ocimum leaf extract	Pulse beetle control by replacing toxic insecticides	(Hemalatha *et al.*, 2024)

TABLE 17.2 Summary of the different NP types, applications, and their effects on plants.

NP type	Concentration	Vegetal	Application	Effect	Reference
Fe-OH bio-composite	121.5 mg g^{-1}	*Emblica officinalis* Gaertn or *Phyllanthus emblica* Linn	Water treatment	Bio-adsorbent	(Deshmukh, Sar, and Jindal, 2023)
Nano-Se	5 mg L^{-1}	*Cucumis melo* l.	Foliar	Biostimulant	(Kang *et al.*, 2022)
Nano-K	5 mg L^{-1}	*C. pepo* L.	Foliar	Biostimulant	(Rady *et al.*, 2023)
Nano-Se	10 mg L^{-1}	*Salvia miltiorrhiza*	Foliar	Biostimulant	(Zhang *et al.*, 2023)
Nano-SiO_2/CeO_2	100-500 mg L^{-1}	*Sedum spectabile*	Soil	Bioremediation	(Liu *et al.*, 2023)
Nano-TiO2	10 mg kg^{-1}	*Vigna unguiculata* (L.) Walp.	Foliar	Bioremediation	(Ogunkunle *et al.*, 2020)
Niossomas	5.5 mg L^{-1}	*Lippia citriodora*		Nano-preservative	(Saleh *et al.*, 2022)
Nano-Cu		*Medicago sativa*	Soil	Nano-fertilizer	(Cota-Ruiz *et al.*, 2020)
Nano-CuO and Nano-ZnO	300 mg kg^{-1}	*Hordeum vulgare*	Soil	Nano-fertilizer	(Jośko *et al.*, 2021)
Nano-ZnO, nano-FeO and nano-MgO	40 mg kg^{-1} (Fe and Mg) and 100 mg kg^{-1} (Zn)	*Caesalpinia bonducella*	Soil	Nano-fertilizer	(Khalid *et al.*, 2022)

and phytopathogens (Zhang *et al.*, 2023; Kang *et al.*, 2022). Another study investigated squash (*Cucurbita pepo* L.) cultivated under saline stress and treated with potassium NPs. The parameters, such as number of leaves per plant, leaves area per plant, shoots fresh weight, and shoots dry weight, increased by 16.0, 11.0, 17.2, and 16.8%, respectively. The characteristics attributed to yield, such as number of fruits per plant, fruit yield per plant, and total fruit yield per hectare, were higher, between 13.1 and 13.6%. The fruit quality indicators were superior to the control by 15.1% (vitamin C content), 11.8% (total soluble solids), 0.2% (acidity), and 28.5% (soluble sugar content) (Rady *et al.*, 2023).

Zhu *et al.* (2024) utilized waste milk to develop an agricultural nano-fertilizer. The waste was converted into fulvic acid and humic acid through an artificial humification process, using persulfate activated by potassium hydroxide. The application of the nano-fertilizer promoted chickweed growth, resulting in a fresh plant weight of 2.19 g, compared to 1.05 g in the control group (without nano-fertilizer application) after 21 days of treatment. Similarly, the fertilizer treatment stimulated leaf development by 104% compared to the control. The average root length was also influenced by the addition of the nano-fertilizer, with plant roots reaching 10.11 cm, whereas the control had a root length of 6.39 cm, demonstrating the fertilizer's effect on promoting root elongation (Zhu *et al.*, 2024). Drinking water industry waste also was reported to synthesize nano-fertilizers. The soil treated with fertilizer synthesized in the 3:1 ratio showed a water retention capacity 9.3 times greater than soil treated with conventional fertilizer after 26 days. The synthesized fertilizer exhibited lower leaching and loss of nutrients, such as phosphorus, potassium, and magnesium, than traditional fertilizers (Elsabagh, Elkhatib, and Rashad, 2024).

Abdel-Aziz *et al.* (2021) produced nitrogen, phosphorus, and potassium (NPK) nanocomposites from industrial waste for application as foliar fertilizer. The nitrogen was extracted from chitosan from shrimp shells and squid pin waste. The phosphorus was derived from bovine bone, and potassium was obtained from banana peels. The nano-NPK fertilizer, produced using an eco-friendly approach, was tested at concentrations of 10%, 25%, 50%, and 100% and applied to the leaves of *Capsicum annuum* L. cv. Cordoba plants. The NPK nanocomposites at a concentration of 25% promoted the growth, productivity, and harvest of *C. annuum* L. compared to the control (chemical fertilizer treatment).

Nanotechnology can also improve seed germination in the sensitization stage (nano-priming). Applied NPs can reduce the germination rate or even improve seed stress tolerance by regulating reactive oxygen species (ROS). The effect of NPs influences the growth, quality, yield, and homeostasis of ROS in plant seeds (Kandhol *et al.*, 2022). Wheat seeds were

submitted to nano-priming treatment and showed greater drought tolerance. The NPs protected the PSI and PSII complexes that directly participate in photosynthesis. After germination, the nano-conditioned plants maintained a better physiological state of PSII under water stress. Therefore, nanotechnology contributes to higher protection of the plant's photosystems (Kalal, Tomar, and Jajoo, 2022).

Using Cu as a fertilizer and pesticide in agriculture causes accumulation in the environment. Thus, applying Cu-based NPs proved to reduce the release of the compound in the ecosystem. Nano Cu compounds can act as nano-fertilizers, promoting the improvement of the mass and length parameters of the shoots and roots of the plant. In addition, an increase in the concentration of Fe and Zn in the roots and the content of Fe in leaves was verified, as well as an increase in microorganisms responsible for the absorption of specific elements for the development of the plant (Cota-Ruiz *et al.*, 2020). Sedefoglu, Zalaoglu, and Bozok (2022) studied the application of ZnO NPs as a nano-fertilizer in cultures of *Lepidium sativum* (watercress). The authors showed that the lowest dosage of nano-fertilizer (250 ppm) promoted greater radicle growth and plumule length in watercress at rates of 45% and 41%, respectively, compared to the control assay (without nano-fertilizer). Moreover, the wet and dry weight of the vegetable increased by 16% and 33%. These results showed that fertilizers are efficient for growing plants and vegetables in lower concentrations than chemical fertilizers. This fact is crucial for the environment, process costs, and yields. Jośko *et al.* (2021) also studied the effects of applying Cu and Zn NPs, individually and combined, and metallic salts. After treatment, the concentrations of Cu and Zn were higher in the individual application in the soil, resulting in the regulation of genes related to the absorption of metals. The nanostructures also promoted the gradual release of metals. These results demonstrate the potential of nanotechnology in the development of nano-fertilizers.

Nanotechnology can be used to reduce the absorption of potentially toxic compounds such as cadmium (Cd). TiO_2 NPs reduced the absorption and translocation of Cd in cowpea plants, causing less stress to the plant. The activities of enzymes related to the prevention of oxidative stress, such as ascorbate peroxidase and catalase, were increased in roots and leaves after application. The content of micronutrients Zn, Mn, and Co increased in seeds. Lower cadmium absorption reduces the toxicity of the metal for consumption (Ogunkunle *et al.*, 2020).

Zinc oxide, iron oxide, and magnesium oxide NPs were prepared and applied to the medicinal plant *Caesalpinia bondducella* to increase yield, nutrients, and chlorophyll content. The results showed an increase in the morphological parameters of the plants from 28 to 50% by conventional fertilizers and from 50 to 93% by the application of NPs concerning the control plants (without the fertilizers and NPs). The chlorophyll content increased from 5 to 28% compared to conventional fertilizers. In control plants, the chlorophyll content increased from 30 to 80%. This study demonstrates the potential for increasing crop productivity through nanotechnology (Khalid *et al.*, 2022).

Adsorbent magnetic nanocomposites were investigated for treating water polluted with uranium (VI). The study shows that nanocomposites obtained by chemical co-precipitation of iron oxide from tree bark (*E. officinalis* Gaertn or *P. emblica* Linn) presented an adsorption efficiency of 90.8%. The sorption process was considered fast, in addition to not producing secondary pollutants, allowing desorption cycles, being endothermic and spontaneous. The study demonstrated the potential of using plants to obtain magnetic particles for treating polluted water (Deshmukh, Sar, and Jindal, 2023).

Metallic NPs have also demonstrated antimicrobial properties. Annona squamosa fruit seed extract was used in the silver NPs manufacture by the green method by reduction of silver nitrate into nanosilver. The metal-based NPs had a potent antibacterial effect against *Streptococcus mutants, Staphylococcus aureus,* and *Escherichia coli* (Muralidharan, Ramesh, and Muthukrishnan, 2023). The ability to reduce silver into nanosilver by the extract due to the presence of phytochemicals can be an alternative for producing antimicrobials with applications in the agri-food sector.

17.6 Mechanism of action of the nanoparticles

The mechanisms of absorption and translocation of NPs applied to plants and seeds are fundamental aspects to be understood as they allow visualizing the accumulation sites and monitoring migration through plant tissues, as well as understanding the chemical and biological parameters that occur after NPs application (Wang *et al.*, 2023). NPs can be applied during seed preparation and on the above-ground or root parts of plants in various ways, including foliar spraying, stem injection, soil treatment, or hydroponic medium (Singh *et al.*, 2021).

During foliar application, NPs are sprayed onto the leaf surface and absorbed through cuticular and stomatal pathways, with translocation to other tissues occurring through the phloem and xylem (García-Ovando *et al.*, 2022). The absorption of NPs by plants via foliar route depends on size, shape, surface functionalization, chemical composition, exposure time, and nanomaterial stability (Proença *et al.*, 2022). The size and composition of NPs determine the site of foliar absorption, as lipophilic substances with a size smaller than 4.8 nm enter through cuticular diffusion. However, polar and hydrophilic

substances are absorbed through stomatal pores that range between 10 and 100 nm (Wang *et al.*, 2023; Kapoor *et al.*, 2022).

Ikhajiagbe, Igiebor, and Ogwu (2021) biosynthesized silver NPs using plant extracts for foliar application on rice plants (*Oryza sativa,* Poaceae). Effects were observed in the agronomic parameters of plants exposed to silver NPs, such as increased plant and leaf length, root elongation, greater number of roots, and yield. According to Miranda-Villagómez *et al.* (2019), the use of silver NPs can enhance photosynthetic pigments and growth parameters in rice plants due to increased physiological efficiency in water use, nutrient absorption and retention, and an increase in photosynthetic rate.

Applying NPs in the soil as nano-fertilizers results in a more complex interaction with plant roots than foliar absorption. The mechanism of NPs' absorption in the soil begins at the root surface in two ways: NPs can penetrate the root hair cuticle due to its weak development, or the negative charges on root hairs enable the accumulation of positively charged NPs, contributing to root absorption (Schwab *et al.*, 2016; Lv, Christie, and Zhang, 2019). After penetration into the roots, the translocation of NPs from the epidermis to the shoots can occur through the xylem via aquaporins and transport proteins. The movement of NPs within plant cells can occur through both apoplastic and symplastic pathways (Kapoor *et al.*, 2022).

The apoplastic pathway allows NPs to migrate radially within plant tissues, potentially reaching the aerial part of the plant. The symplastic transport occurs through the phloem pathway, where NPs enter the cytoplasm and are transported between cells through plasmodesmata, facilitating the distribution of nanomaterials to non-photosynthetic tissues and organs (Wang *et al.*, 2023; Pérez-de-Luque, 2017). This system of NPs absorption and translocation in plant roots depends on the size, surface charge, and chemical composition of the particles. Additionally, NPs can be applied in seed treatment as nano-priming. The mechanism of action of NPs occurs by penetrating the seed pores and triggering plant hormones. This nano-fertilizer system accelerates seed germination and seedling growth (Sharma *et al.*, 2023).

17.7 Challenges

The direct release of nanostructures into the environment from agricultural activities and the possibility of nanostructures migrating through the food chain are topics of great concern (Mittal *et al.*, 2020). NPs can enter the body through ingestion, inhalation, or skin contact. Structures on a nanometric scale have a high surface area that contributes to their dispersion and penetration into cells. In addition, nanomaterials are similar in size to DNA, promoting the chances of reacting with biological specimens. Therefore, the interaction of nanostructures within the human body is another concern, as they can cause oxidative damage and toxicity (Neme *et al.*, 2021). There is an urgent need to clarify the safety of these nanomaterials for health. Moreover, to establish the benefits of nanotechnology in agriculture, it is also necessary to improve the regulation for commercializing nanoproducts such as nano-pesticides and nano-fertilizers (Mittal *et al.*, 2020).

The interaction between the nanostructure and the plant is an essential important point in understanding the physiological and biochemical responses imposed by plants. In this sense, emerging techniques contribute to localizing and quantifying nanomaterials throughout the plant system, giving an idea of their transformation and safety aspects in a complex system (Mittal *et al.*, 2020). The nanoparticle determination or other nanostructures released in the environment and their accumulation in plants is also essential to solidify nanotechnology in agriculture (Rajput *et al.*, 2018). Another challenging issue in agriculture is climate variability, which drives the inclusion of new agricultural systems that can withstand droughts, heat, and other environmental stresses (Elias *et al.*, 2019). Thus, a broad perspective of nanotechnology is essential to fulfill the objective of helping to promote global agriculture (Mittal *et al.*, 2020).

17.8 Conclusion and future perspectives

Nanotechnology is one of the promising areas to produce new products for beneficial purposes in agriculture. Using NPs from agricultural and industrial wastes for developing nano-pesticides and nano-fertilizers contributes to increasing crop productivity, reducing costs and the loss of nutrients to soil and water bodies, in addition to improving soil quality. The prospective use of wastes and nanoscale agrochemicals, such as nano-fertilizers and nano-pesticides, has transformed traditional agricultural practices, making them more sustainable and efficient.

NPs can be applied to plants in various ways, such as foliar spraying, soil treatment, and seed treatment. Therefore, it is essential to comprehend the absorption and translocation mechanisms of NPs in plants and seeds, as this system impacts plant productivity and yield. Furthermore, factors such as size, charge, and chemical composition of NPs influence the site of absorption, accumulation capacity, and migration in plants. The main challenges encountered in using nanomaterials in agriculture are their migration into the food chain, release into the environment, and plant accumulation. Thus, there is an urgent need to clarify the safety of these nanomaterials for health and the environment and improve the regulation for commercializing nanomaterials for the agricultural sector.

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Part IV

Waste valorisation and resource utilisation

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Chapter 18

Nutrient recovery and recycling: Extracting and reusing nutrients from agricultural waste

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Chapter Outline

18.1. Introduction **283**
18.2. Agricultural waste as a nutrient source 285
18.3. Nutrient extraction techniques 288
18.4. Nutrient recovery technologies 290
18.5. Applications 294
18.6. Challenges and barriers 296
18.7. Conclusion and future perspectives 297
References **297**

18.1 Introduction

Growing demand for food production due to the exponential population rise globally necessitates intensive farming practices. Such agrarian operations ultimately lead to extensive amounts of agricultural waste generation in the forms of dairy excreta, crop residues, food processing, and hazardous waste, including leftover chemical fertilizers and pesticide residues (Koul, Yakoob, and Shah, 2022; Obi, Ugwuishiwu, and Nwakaire, 2016). By 2050, the amount of waste is projected to reach 3.4 billion tons annually, and the agriculture sector will be the prime contributor to waste generation globally (Peng *et al.*, 2023). Developing nations, such as India, generate millions of tons of waste annually, and the wastes in a significant proportion of India are derived from crop production and allied sectors (Khaire, Moholkar, and Goyal, 2021). This gigantic amount of waste, more precisely agricultural waste, is associated with environmental nuisances and disease transmission and thus requires proper disposal and eco-friendly sustainable management (Mishra *et al.*, 2023).

In developing countries, there is a serious deficit of adequate infrastructure, eventually leading to poor handling and management of agricultural waste. As an immediate effect, there is growing suffering from environmental pollution due to frequent crop residue burning, landfilling, or dumping. For example, 92 metric tons of crop residues are being burned annually in India, which causes severe air pollution and contributes to global warming (Bhuvaneshwari, Hettiarachchi, and Meegoda, 2019). In addition, landfilling or dumping of agricultural waste has led to groundwater contamination

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(Waqas *et al.*, 2023) and can cause serious health hazards in humans directly or indirectly (Negi, Mor, and Ravindra, 2020). These (mal)practices eventually lead to a gradual loss of natural resources due to improper resource utilization, recycling, and management. Consequently, it also promotes an ill ecological cycle, which is presently considered a burning issue and the biggest challenge for human existence (Thorat *et al.*, 2015).

Resource utilization sustainably is one of the central aims of the United Nations' (UN) Sustainable Development Goals (SDGs) (Sarkodie, 2022). In particular, the newer approach, popularly known as circular bio-economy, is emerging and gaining popularity throughout the globe. The central workflow of circular bio-economy is to build a strategic model that integrates waste management and the valorization process and operates synergistically to facilitate the recycling and regeneration of resources from waste (Awasthi *et al.*, 2022). For instance, valorization of agricultural waste includes the production of bio-energy, bio-fuel, bio-polymers, and agricultural bio-inputs, such as composts, manures, bio-fertilizers, bio-pesticides, etc., which are of high commercial value and demand (Capanoglu, Nemli, and Tomas-Barberan, 2022; Puglia *et al.*, 2021). Organic waste can also play a pivotal role in sustainable farming due to its multifaceted roles as bio-inputs of plant nutrients, organic matter, hormones, plant beneficial microbes, bio-control agents, soil amendments, and several others (Rodríguez-Espinosa *et al.*, 2023). See the illustration for the visual workflow of circular bio-economy operating waste recycling and nutrient recovery in agriculture (Figure 18.1).

However, utilizing agricultural waste as a source of plant nutrients requires efficient nutrient extraction and recycling technologies that aim to achieve limited or no nutrient loss during conservation and recovery. In addition, the technologies must ensure quality plant nutrients while recovering as per standard without compromising environmental concerns and health safety. Several traditional and well-equipped modern techniques are optimized to recover nutrients from organic wastes. In this context, this chapter briefly highlights potential sources of agricultural wastes and their nutrient content. Further, it expands elaborately on methods of nutrient extraction and recovery technologies. In particular, the Indian traditional knowledge of waste management concerning nutrient recycling and recovery in agriculture is the unique theme of this chapter. Finally, this chapter discusses downstream applications of agricultural wastes while addressing the limitations of these technologies.

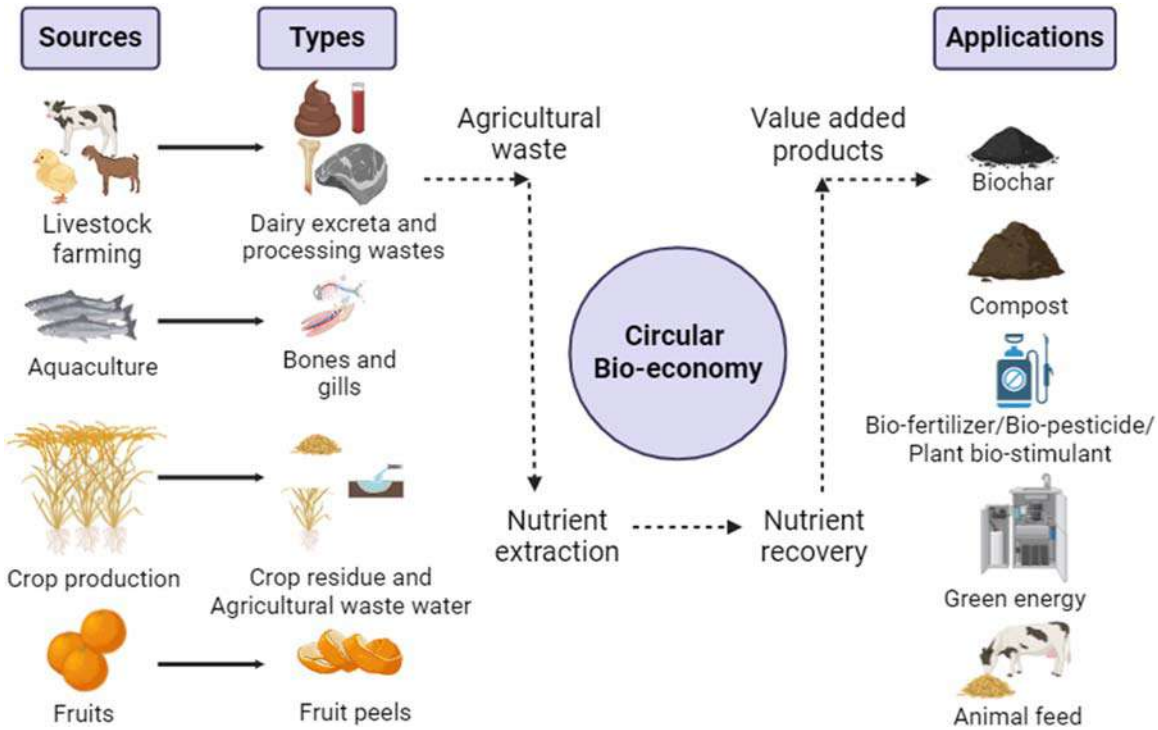


FIGURE 18.1 A schematic diagram illustrates the workflow of agricultural waste management. Agricultural waste management involves screening different types of farm waste and their sources. Based on this information, suitable physical, chemical, and biological methods of nutrient extraction and recovery would be selected. In this circular bio-economy, waste valorization is a value-added step before their various downstream applications in agriculture and other allied sectors. The cartoons were adopted from the BioRender software (trial version), and the figure was prepared accordingly.

18.2 Agricultural waste as a nutrient source

18.2.1 Potential sources of agricultural waste

To plan target-specific strategies for agricultural waste management, the first and foremost step is to identify the potential sources, including their contribution to waste generation. Based on the origin or source, agricultural wastes are grouped into the following types:

18.2.1.1 Crop residue

Agricultural crop residues, in general, are classified into two different classes: "field or on-farm residues" and "process residues." On-farm residues are mostly crop parts, such as leftover straws, stalks, stems, and leaves on the field after harvesting. On the contrary, process residues generated as processed byproducts of crops include husks, bagasse, seeds, and roots (Demirbas, 2011). Interestingly, a considerable crop residue remains unutilized and seeks immediate attention to avoid residue burning (Zhu *et al.*, 2023). Approximately 3.8 billion metric tons of crop waste are produced each year in India, of which cereals (74%) contribute the maximum, followed by sugar crops (10%), pulses (8%), tubers (5%), and oil seeds (3%) (Lal, 2005). Rice is a global staple food crop responsible for 731.3 metric tons of straw generation, of which Asia contributes approximately 667.6 metric tons annually (Sarkar *et al.*, 2012). India, one of the largest rice producers, is expected to generate 221.8 metric tons of rice straw yearly by 2030 (Kumar *et al.*, 2018). On the other hand, as a primary byproduct of wheat processing, approximately 529 million tons of wheat straws are generated globally (Tufail *et al.*, 2021). Corn stover is the residue of leaves, stalks, cobs, and husks and is estimated to produce 1 billion tons per year globally (Ruan *et al.*, 2019). These, together, reinforce the proper handling of crop residue waste and its processing for downstream applications.

18.2.1.2 Livestock waste

Based on the projection of the world population, livestock and poultry numbers could reach approximately 100 billion by 2050 to meet the global demand for meat, egg, and dairy products (Yitbarek, 2019). The 19th Livestock Census data reveals that the Indian livestock population accounts for about 512.05 million and produces 1095 million metric tons of dung annually (Parihar *et al.*, 2019). In addition, another study revealed that approximately 23.2 to 33.0 L of urine is excreted per cattle per day (Edwards *et al.*, 2015). These statistical data, together, indicate a significant amount of excreta generation as byproducts in livestock farming. Apart from excreta, other associated byproducts in livestock and poultry farming require proper waste management and recycling. In particular, in the case of poultry production, blood, infertile eggs, broken eggshells, feathers, dead embryos, and birds are produced, including poultry litter (Prabakaran and Valavan, 2021). A large proportion of livestock farming includes meat production, and cattle, buffaloes, swine, goats, and sheep are popular meat sources globally. Hence, animal byproducts in the slaughterhouse, such as skins, blood, bones, hoof, horns, and hides, are produced daily during meat processing (Irshad and Sharma, 2015). These protein-rich animal wastes are widely popular for their various value-added and other applications.

18.2.1.3 Agricultural wastewater

A significant proportion of waste, in reality, ends up in the wastewater stream (Salgot *et al.*, 2006). Globally, 400 billion m^3 of wastewater is discharged annually and frequently mixed with domestic, industrial, and agricultural waste (Rusănescu, Rusănescu, and Constantin, 2022). Agricultural wastewater originates from different sources, such as units of crop production, dairy, poultry, aquaculture, and food processing, and it is contaminated heavily with organic wastes along with minerals, nutrients, pesticides, antibiotics, and toxic metals (Ali, Fahmy, and Elhefny, 2021; T. Wang *et al.*, 2018). High organic matter further accentuates microbial contamination, including waterborne emerging pathogens, multidrug resistance, and antifungal tolerance. The higher organic matter, nutrients, and minerals in agricultural wastewater, including its possible negative impacts on ecology, urgently seek specific waste recycling technologies and management.

18.2.1.4 Food processing byproducts

Food processing is the growing sector that links food production to human consumption. Due to the ever-increasing demand for processed foods, significant food processing wastes generated in recent years have the potential to pollute the environment due to their large volume and chemical oxygen demand (COD) (Gonçalves and Maximo, 2023; Hansen and Cheong, 2007; Waldron, 2009). Around 89 million tons of food waste have been reported in the European Union (EU), with a further projection of a 40-fold rise in upcoming years. According to the Food and Agriculture Organization (FAO), 40% of food production leads to waste in India (H. Kumar *et al.*, 2020). Such food loss is directly or indirectly related to

issues with storage, transportation, and processing (Torres-León *et al.*, 2018). For instance, fruit and vegetable processing from agro-industries or daily household activities generates significant food waste. In particular, the non-edible parts of fruits or vegetables, such as peels, pods, seeds, and skins, contribute to waste, constituting approximately 10 to 60% of the fresh produce (Sharma, Oberoi, and Dhillon, 2016).

18.2.1.5 Aquaculture waste

Aquaculture waste includes two broad classes, that is, aquaculture sludge and fish processing waste. Aquaculture sludge is, in fact, a combination of residual fish feed and feces, whereas fish processing waste comprises fish fins, heads, scales, viscera backbones, and tails (Wu and Song, 2021). According to the report of the FAO, 9.1 million tons of fish processing waste are being disposed of each year (Roda *et al.*, 2019). In particular, fish processing operations in India generate approximately 4 million metric tons of waste, of which shrimp processing yields the highest (Nanda *et al.*, 2022).

18.2.1.6 Floriculture-derived byproducts

Flowers have different applications in various industries, such as perfume, food, cosmetics, beverages, and textiles. In addition, flowers also receive traditional acceptance for daily religious and social purposes (Waghmode *et al.*, 2018). In India, 870 metric tons of loose flowers and 4,341 metric tons of cut flowers are produced annually (Dasgupta and Dadlani, 2011). Approximately 80% of flowers, irrespective of whether sold or unsold, end up in the garbage or in water bodies (Waghmode *et al.*, 2018).

18.2.2 Nutrient composition of different agricultural wastes

Agricultural waste, irrespective of its difference in origins, plays a pivotal role as an alternate source of essential and beneficial nutrients required for plant growth and development. Based on the requirement for normal and healthy plant growth and their functions, plant nutrients are classified into four categories, i.e., primary macro-, secondary macro-, micro-, and beneficial nutrients. However, the plant requires both macro- and micronutrients for its growth and development, and any deficiencies in plant nutrients lead to aberrant physiological growth and diseases. This section illustrates agricultural waste as a potential source of these four classes of plant nutrients.

18.2.2.1 Primary macronutrients

Plant primary macronutrients are nitrogen (N), phosphorus (P), and potassium (K). In modern agriculture, inorganic fertilizers are the main source that provides the necessary amount of primary macronutrients. However, due to potential environmental concerns and gradual resource depletion, agricultural wastes are increasingly instrumental as an alternate flow of nutrients that can be recycled and applied directly to crop fields. Table 18.1 summarizes the nutrient content of different types of agro-waste.

TABLE 18.1 Macro-, micro-, and beneficial plant nutrient content of different agricultural wastes.

I. Macronutrient content of different agricultural wastes:

		Primary macronutrient			Secondary macronutrient			
Type of waste	Source of waste	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	References
Straw	Rice	0.83	0.27	2.06	-	-	-	(Shao *et al.*, 2023)
	Wheat	0.62	0.16	1.23	-	-	-	
	Maize	0.87	0.31	1.34	-	-	-	
	Soybean	1.63	0.39	1.27	-	-	-	
	Cotton	0.94	0.33	1.10	-	-	-	
	Peanut	1.66	0.34	1.19	-	-	-	
	Rapeseed	0.82	0.32	2.24	-	-	-	

TABLE 18.1 Macro-, micro-, and beneficial plant nutrient content of different agricultural wastes.—cont'd

I. Macronutrient content of different agricultural wastes:

Type of waste	Source of waste	Primary macronutrient			Secondary macronutrient			References
		N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	
Manure	Dairy cow	0.27	0.20	0.80	0.27	0.11	-	(Weiland, 2001)
	Beef cow	0.30	0.20	0.47	0.17	0.11	-	
	Calf	0.39	0.27	0.68	0.26	0.10	-	
	Pig	0.53	0.40	0.40	0.40	0.13	-	
	Poultry/Layer	0.46	0.50	0.30	1.10	0.10	-	
Processing waste	Mustard oil cake	4.70	1.06	0.91	-	-	0.93	(Sultana *et al.*, 2021)
	Sugarcane press mud	1.59	0.09	0.64	-	-	0.51	
	Apple pomace	0.61	0.07	0.19	-	-	-	(Krasowska and Kowczyk-Sadowy, 2022)
	Carrot root	0.64	0.38	2.83	-	-	-	
	Onion husks	1.7	0.21	1.48	-	-	-	
Vegetable waste	Potato peel	-	-	3.77	0.14	0.14	-	(Biswas *et al.*, 2021)
	Cucumber peel	-	-	3.75	0.70	0.26	-	
	Unripe banana peels	-	-	4.52	0.40	0.12	-	
	Cauliflower stem	-	-	10.52	1.75	0.27	-	
	Bottle gourd peel	-	-	2.88	0.31	0.14	-	
Fish waste	Tuna processing byproducts	-	0.09 −1.07	1.06 −2.58	-	-	-	(Abbey *et al.*, 2017)
	Tilapia farming solid waste	4.50	2.35	0.24	5.79	0.21	0.44	(Khiari, Kaluthota, and Savidov, 2019)

II. Micronutrient and beneficial nutrient content of different agricultural wastes (mg per g):

Type of waste	Source of waste	Fe	Mn	Zn	Cu	B	Na	References
Vegetable waste	Beet	0.16	0.02	0.12	-	-	3.15	(Khattak and Rahman, 2017)
	Mustard	0.23	0.02	0.05	-	-	0.79	
	Carrot	0.29	0.06	0.11	-	-	2.06	
	Sweet potato	0.10	0.16	0.21	-	-	2.83	
	Radish	0.27	0.08	0.17	-	-	3.61	
	Potato	0.11	0.03	0.09	-	-	2.06	
	Ginger	0.53	0.18	0.16	-	-	1.10	
	Cucumber	0.08	-	0.05	0.01	3.35	2.03	(Biswas *et al.*, 2021)
	Banana	0.06	-	0.04	0.01	0.89	0.63	
	Cauliflower	0.07	-	0.04	0.01	8.75	2.30	
	Bottle gourd	0.12	-	0.03	0.01	2.97	0.71	

The references are cited in Table 1.

18.2.2.2 Secondary macronutrients

In comparison to N, P, and K, plant nutrients, such as calcium (Ca), magnesium (Mg), and sulfur (S), are required in comparatively smaller amounts and are thus regarded as secondary macronutrients. From the crop management point of view, secondary macronutrients are needed in smaller amounts than primary ones and hence are not added into the soil separately (Zewide and Melash, 2021). In this context, agricultural wastes may provide a better option as a source of slow-releasing secondary macronutrients as per the requirement of crops. Table 18.1 indicates the different sources of these elements in agricultural waste.

18.2.2.3 Micronutrients

Micronutrients required for plant growth and development are iron (Fe), copper (Cu), manganese (Mn), molybdenum (Mo), nickel (Ni), chlorine (Cl), boron (B), and zinc (Zn). According to Biswas *et al.* (2021) and Khattak and Rahman (2017), vegetable peels are excellent sources of micronutrients, such as Cu, B, Fe, Mn, and Zn (Table 18.1). Cow dung, widely used in agriculture to supply plant nutrients, is also the source of several micronutrients, that is, Fe, Cu, Mn, and Zn (Dhiman *et al.*, 2021; Vijayaraghavan *et al.*, 2016). In addition, recycled crop residues such as composts, manures, and other bio-inputs for agricultural applications can also provide plant micronutrients (Sarma, Chakravarty, and Bhattacharyya, 2013). Growing evidence suggests that fish byproducts are sources of Cu, Fe, Zn, and Mn (Abbey *et al.*, 2017; Khiari, Kaluthota, and Savidov, 2019).

18.2.2.4 Beneficial nutrients

The notable beneficial nutrients in plants are cobalt (Co), vanadium (Va), sodium (Na), and silicon (Si), which confer improved plant growth and biotic and abiotic stress tolerance (Kirkby, 2023). Rice husk, one of the most abundant byproducts in agriculture, is a rich source of Si (Yalcin and Sevinc, 2001). Studies have also reported that shields of melons, groundnuts, and beans contain the beneficial element Na (Musa, Augustine, and Akpomie, 2022). Similarly, vegetable peel waste is also a good source of Na (Table 18.1).

18.2.3 Organic matter content

The depletion of organic matter in the soil leads to an adverse impact on soil health and fertility, which is a considerable threat to food production (Gayathri *et al.*, 2020). Humic substances are primary organic constituents of soil and are formed by the degradation of animal and plant residues (Schnitzer and Khan, 1975). In situ decomposition of crop residue increases the humic acid content of the soil (Singh, Beri, and Sidhu, 1995), which may influence the long-term fertility of agricultural soil. In support of this observation, the findings of Gayathri *et al.* (2020) have suggested that different agro-industrial wastes are the source of humic acid substances. This study has also found that fulvic acid, another intermediate of organic matter, can be extracted from agro-industrial wastes (Gayathri *et al.*, 2020).

18.2.4 Other bioactive compounds

Different bioactive substances, such as phenolics, phytohormones, proteins, and free amino acids, can be derived from agricultural wastes (Puglia *et al.*, 2021; Zhmyrko *et al.*, 2024). On the other hand, a group of plant bio-stimulants, such as phenolics, have been found in peels of fruits and vegetables (Sadef *et al.*, 2022). Similarly, phytohormones have been reported in composts prepared from wastes of agro-food industries (Sienkiewicz *et al.*, 2024). Together, agricultural wastes are a valuable source of several bioactive compounds of commercial interest.

18.3 Nutrient extraction techniques

With a better knowledge of agricultural wastes, their potential sources, and nutrient content, the next essential step is to extract those nutrients from waste for various downstream applications. Nutrient extraction primarily involves two steps: the separation and subsequent enrichment of nutrients available in different agricultural wastes. Since the extraction process varies considerably based on sources of waste and types of nutrients, this section discusses different methods of nutrient extraction.

18.3.1 Physical methods

Physical methods of nutrient extraction involve the initial screening of agricultural wastes, followed by their size reduction for better nutrient extraction. Several physical methods, namely membrane filtration, distillation, and microwave-assisted methods, are commonly used for nutrient extraction from waste.

18.3.1.1 Mechanical separation

Mechanical separation is the process of separating liquid and solid fractions of waste that exploits the physical characteristics of particles based on differences in size, density, shape, and others (Pantelopoulos and Aronsson, 2021).

18.3.1.2 Size reduction technologies

In this method, grinding, crushing, shredding, etc., are employed to reduce the size or volume of the organic wastes. Reducing the particle size, in turn, increases the surface area of the particle fragments, which eventually helps microbes break down the complex organic matter. An interesting study on the impact of size on the composting process demonstrated that reducing the size of organic waste accelerates the decomposition process and enhances both the macro- and micronutrient content of the compost (Haynes, Belyaeva, and Zhou, 2015).

18.3.1.3 Membrane filtration

Membrane filtration is another physical method that employs the size and solubility of the particles in water to separate from each other. Micro-, ultra-, nano-filtration, and reverse osmosis are well-known membrane filtration techniques to accumulate and extract nutrients from wastewater (Mehta *et al.*, 2015). The utility of membrane filtration techniques to extract nutrients from anaerobic digester waste streams is well studied and assessed. Studies also revealed that ultra-filtration followed by a nano-filtration technique was effective for P recovery, while NH_3 separation was less effective. Overall, there are considerable efforts to improve the efficiency of membrane filtration techniques in nutrient extraction (Zacharof *et al.*, 2019).

18.3.1.4 Electro-dialysis

Electro-dialysis is a membrane-based filtration technique that utilizes an electric field and selectively separates nutrients mostly from wastewater (Xie *et al.*, 2016). A study claims that a 2.9-fold high N, 2.7-fold high P, 3.1-fold high K, and other micronutrients were obtained from urine samples subjected to electro-dialysis (Pronk, Biebow, and Boller, 2006). In addition, a modified electro-dialysis technique can separate divalent ions from monovalent ones. This technique has successfully demonstrated the fractionation of sulfate (SO_4^{2-}) from chloride (Cl^-) in wastewater treatment (Zhang *et al.*, 2012).

18.3.1.5 Microwave-assisted method

Microwave-assisted extraction usually couples with the solvent extraction technique and utilizes microwave energy to release different classes of compounds from waste (Amran *et al.*, 2021). This technique, in principle, relies on molecular agitation induced by microwaves through ionic conduction and dipole rotation (Sparr Eskilsson and Björklund, 2000). This technology is appropriate for extracting bioactive compounds, such as phenolics, antioxidants, essential oils, and others (Proestos and Komaitis, 2008; Saoud, Yunus, and Aziz, 2017; Xiao *et al.*, 2009).

18.3.1.6 Membrane distillation

Membrane distillation principally differs from the distillation process. This technique rather involves the separation of molecules through a microporous hydrophobic membrane at a high temperature (Alkhudhiri, Darwish, and Hilal, 2012). For instance, membrane distillation on aquaculture wastewater treatment effectively recovers NH_3, P, and K at almost five times higher than the initial concentration (Teoh *et al.*, 2022). A similar study claimed to recover NH_3 and P from municipal wastewater while assessing two different membrane distillation configurations for their nutrient extraction efficiency. The observations suggest that direct contact membrane distillation performs better in higher pH wastewater, while in low pH, vacuum membrane distillation is more suitable (Simoni *et al.*, 2021).

18.3.2 Chemical methods

Chemical methods primarily employ the chemical properties of molecules, such as precipitation, chelation, solubility, etc., for nutrient extraction from waste. The following are the chemical methods commonly utilized for this purpose.

18.3.2.1 Acid digestion

Acid digestion plays a critical role in nutrient extraction from agricultural waste as it helps in organic matter decomposition, nutrient mineralization, compound solubilization, and trace element dissolution.

18.3.2.2 Solvent extraction

Solvent extraction is a widely accepted method in the valorization process of agricultural waste. In principle, it relies on extraction based on different solubility of chemical compounds. This method is commonly used for extracting bioactive compounds, such as phenolics and flavonoids (Munir *et al.*, 2018; Sagar *et al.*, 2018). Although solvent extraction techniques are highly efficient, environmental concerns of toxicity associated with these techniques can be challenging to tackle. To avoid this, green extraction techniques have also received attention recently (Amran *et al.*, 2021).

18.3.2.3 Chelation

Chelation plays a pivotal role in nutrient extraction by enhancing solubility, selectivity, and stability. It involves chemical agents to mediate chelate formation with metal ions. Chelating resins are a potential tool for extracting trace elements from wastewater. For instance, Zn has been recovered successfully from industrial wastewater using the chelation technique (Hirai, 1984; Uejima, Hirai, and Ishibashi, 1978).

18.3.2.4 Chemical precipitation

The chemical precipitation technique is employed to precipitate and isolate nutrients selectively from wastewater. For example, chemical agents selectively targeting Fe can react and precipitate out nutrients from the stream. On the other hand, Al and Fe-based precipitating agents are popular in this technique for P extraction from wastewater. Similarly, precipitating agents, such as Ca or organic polymers, are also used in this process (Mehta *et al.*, 2015). In this context, struvite precipitation is a widely used chemical precipitation technique to recover NH_3 and P (Siciliano *et al.*, 2020; Yetilmezsoy and Sapci-Zengin, 2009). We have discussed, in detail, the struvite precipitation technique from wastewater in the nutrient recovery section.

18.3.3 Biological methods

The biological nutrient extraction process is normally carried out either by the living organism itself or through the actions of biological products. These methods are usually cost-effective and environmentally friendly. This section describes two notable techniques of biological nutrient extraction: microbial degradation and enzymatic hydrolysis.

18.3.3.1 Microbial degradation

Microbe-mediated bio-conversion of agricultural waste is a promising tool for waste recycling and valorization (Singh and Singh, 2022). Microbes are the key players that degrade the organic matter of agricultural waste (Singh and Singh, 2022) and release diverse classes of nutrients and bioactive compounds (Insam, Franke-Whittle, and Goberna, 2010). For example, several bacteria, actinomycetes, and fungi produce hydrolytic enzymes, such as cellulases, laccases, and amylases, and depolymerize complex organic materials into simpler compounds (Singh *et al.*, 2013). This nutrient extraction method is an economical and ecologically beneficial approach that restores agroecosystem health and promotes the sustainability of crop farming (Upadhyay *et al.*, 2024).

18.3.3.2 Enzymatic hydrolysis

Enzymatic hydrolysis, in contrast, involves specific and regulated degradation of complex organic compounds with the help of biologically active enzymes. This approach is also safe and environmentally friendly for producing value-added products from organic waste (Araujo *et al.*, 2021). This method employs a variety of enzymes in the waste valorization process, including proteases and lipases. For instance, protease treatment of organic wastes produces protein hydrolysates of intermediate di- or tripeptides of amino acids. Protein hydrolysates are high-value products with multifaceted roles in nutrition, biotechnology, and agriculture (Angulo and Márquez, 2023). It is also important to note that different classes of phosphatase enzymes have shown their potential to recover P from organic wastes (He, Griffin, and Honeycutt, 2004).

18.4 Nutrient recovery technologies

Nutrient extraction and recovery are related but differ from each other in the context of waste valorization. Nutrient recovery mainly emphasizes the reuse of the available nutrients in agricultural wastes and can be directly recommended in agriculture and other domestic and commercial applications. This section highlights modern nutrient recovery techniques, including traditional knowledge to convert "waste into wealth."

18.4.1 Nutrient recovery from liquid fractions

Agricultural wastewater is an integral and crucial part of modern agriculture. Different technologies involved in nutrient recovery from such liquid fractions are illustrated below.

18.4.1.1 Struvite precipitation

Struvite precipitation is a selective chemical precipitation method that recovers excess N and P from wastewater (Yetilmezsoy *et al.*, 2017). Struvite ($MgNH_4PO_4 6H_2O$) is a crystal of Mg, N, and P complex with water molecules (Siciliano *et al.*, 2020), and its formation depends on pH and molar ratios of Mg^{2+}, NH_4^+, and PO_4^{3-} ions. Usually, equimolar concentrations of these three molecules are best suited. Interestingly, the wastewater contains Mg^{2+} ions but is too low compared to NH_4^+ and PO_4^{3-} ions. Thus, Mg^{2+} addition into wastewater may selectively precipitate out NH_4^+ and PO_4^{3-} from the stream to form struvite (Lorick *et al.*, 2020). This resultant struvite can be directly used as a slow-release fertilizer, having equal potential to traditional inorganic fertilizers with lesser negative impact (Muhmood *et al.*, 2019).

18.4.1.2 Ammonium recovery

Air stripping or ammonia stripping is a physico-chemical method of N recovery from wastewater and agricultural effluent (Zangeneh *et al.*, 2021). In principle, this technique relies on the mass transfer mechanism that involves the transfer of NH_4^+ molecules from the liquid to the gas phase (Xiang *et al.*, 2020). The released NH_3 is further washed with strong acids, such as sulfuric or nitric acid, to form either ammonium sulfate or nitrate. According to the European Commission, these end products can replace synthetic N fertilizers (Sigurnjak *et al.*, 2019).

18.4.2 Solid-phase nutrient recovery

Solid agricultural wastes, such as crop residues, manures, and food processing wastes, can also be utilized for nutrient recovery. Here, we describe different conventional and modern techniques for nutrient recovery from solid agricultural wastes.

18.4.2.1 *In situ* decomposition

In situ decomposition involves microbe-mediated decomposition of crop residues, which releases plant nutrients and organic matter directly into the agricultural soil (Zhao *et al.*, 2016). Xia *et al.* (2018) reported an overall improvement in the available macronutrient content of soil due to straw decomposition. Similarly, Wei *et al.* (2015) showed that the incorporation of wheat straw increased the available N (9.1−30.5%), available P (9.8−69.5%), and available K (10.3−27.3%) content of the soil, including improvement of soil enzymatic activities. According to Guan *et al.* (2020), straw incorporation also increases the soil organic C and thus facilitates carbon sequestration. Together, in situ decomposition provides a better option for on-farm recycling to promote the sustainable intensification of agriculture and allied sectors.

18.4.2.2 Composting

Composting is a bio-conversion process that converts organic waste into humus-like substances termed compost. It is a natural microbial decomposition technique that produces soil conditioning agents from waste materials. It also confirms the presence of plant macronutrients (N: 1.2%, P: 0.7%, K: 1.2%) in composts (Ahmed *et al.*, 2019). A recent study on different compost products revealed that these are the sources of plant hormones and have a clear role at critical stages of plant growth (Sienkiewicz *et al.*, 2024). Based on biological agents actively involved in decomposition, composts can be classified broadly as aerobic, anaerobic, and vermicomposting. Aerobic composting is the concerted action of aerobic microbial consortia, and the resultant pathogen-free final product is suitable for agricultural purposes. The anaerobic mode of composting, on the other hand, is mediated by anaerobic bacteria in a closed digester, and their roles in nutrient recovery are promising, particularly in the mode of anaerobic digestion (read the anaerobic digestate section for details). The earthworm-assisted composting process is known as vermicomposting. During vermicomposting, earthworms consume organic waste and eventually decompose the organic matter to produce nutrient-rich composts (Waqas *et al.*, 2023). The benefit of compost application in agriculture depends on its maturity and stability. These are the critical parameters of compost that indicate the degree of the decomposition process. It is well known that complete decomposition facilitates the reduction of phytotoxic elements in the composts, thus ensuring better crop growth and development (Khatua *et al.*, 2018).

18.4.2.3 Pyrolysis

Pyrolysis is the thermochemical decomposition process that converts organic wastes into condensable vapors and pyrolysis char in the absence of oxygen (Bergfeldt *et al.*, 2018; Demirbas and Arin, 2002). This technique directly benefits in two ways: by generating bio-energy and producing soil amendments from organic waste (Pandey *et al.*, 2019). Pyrolysis char or biochar is an organic C-enriched product supplemented with different primary plant macronutrients (Liu *et al.*, 2011). Administration of biochar in agricultural soils has the potential to improve soil quality with controlled nutrient release (Zhang *et al.*, 2010). In support, biochar application has been shown to improve crop productivity in maize, peanut (Yamato *et al.*, 2006), cherry tomatoes (Hossain *et al.*, 2010), rice (Asai *et al.*, 2009), and several other crops. In recent years, there has been growing interest in biochar application in agriculture to improve soil quality and crop productivity.

18.4.2.4 Anaerobic digestate

Anaerobic digestion is a microbe-based organic matter decomposition process in oxygen-free conditions and produces biogas and biomass of microbes (Kelleher *et al.*, 2002). The partially degraded anaerobic digestates as byproducts are rich in plant nutrients and have the potential to replace inorganic fertilizers as soil amendments (Cheong *et al.*, 2020; Dutta *et al.*, 2021). Ries, Chen, and Park (2023) confirmed that administrating anaerobic digestates improves agronomic parameters in lettuce, parsley, and bok choy. On the other hand, there is a growing commercial interest in nonconventional renewable energy, such as biogas, which is suitable for electricity generation and cooking purposes.

18.4.2.5 Landfill waste treatment

Though landfill waste treatment is not directly involved in nutrient recovery, landfill leachate is the source of various plant nutrients. There are techniques suitable for nutrient recycling and recovery from landfill leachate (see the nutrient extraction section).

18.4.3 Indian traditional knowledge

According to Vedic scriptures, traditional Indian knowledge since ancient times in agriculture emphasizes the application of bio-inputs and formulations that aim to maintain the ecological harmony between agriculture and the environment (Mukherjee *et al.*, 2022). These bio-inputs and formulations are the fermented products of dairy excreta and locally available resources (Mahanta and Dhar, 2021). Traditionally prepared formulations can be classified broadly into the following types:

18.4.3.1 Bulky organic amendments

The preparation of bulky organic amendments includes natural resources, such as animal excreta, agricultural residues, and vegetable wastes. The decomposition of such organic wastes releases several plant nutrients and organic matter into the soil. Thus, administrating these amendments enriches soil nutrient availability and enhances soil fertility (Brar, Kaushal, and Bhardwaj, 2019). For instance, *Ghana Jeevamrit* is a type of bulky organic manure and usually utilizes the common principle of composting. The relative composition of *Ghana Jeevamrit* makes it unique among other composts, and it is a 4- to 7-day decomposed product of cattle excreta, jaggery, pulse flour, and virgin forest soil (Singh *et al.*, 2023). *Ghana Jeevamrit* also contains essential plant macronutrients (N: 1.19−1.37%, P: 0.430−0.468%, K: 0.753−0.993%) necessary for plant growth (Sharma *et al.*, 2022).

18.4.3.2 Liquid formulations

Liquid formulations are popular plant bio-stimulants recommended to facilitate better nutrient release ability, enhance soil biology and physico-chemical properties, and improve nutrient uptake compared to solid manures (Martínez-Alcántara *et al.*, 2016; Varshini and Jayanthi, 2020). In India, several ancient liquid formulations are commonly used in agriculture, while other formulations have evolved traditionally over time (Ayangarya, 2005; Chandra *et al.*, 2019). This section briefly discusses the detailed composition, nutrient content, and recommended doses of the traditional liquid concoctions prepared from agricultural wastes.

18.4.3.2.1 Panchagavya *Panchagavya* is the 9-day fermented product of five products of cattle, including dung (500 g), urine (300 mL), milk (200 mL), curd (200 mL), and ghee (100 mL) (Ali, Ghatak, and Ragul, 2011). Since these organic formulations are prepared traditionally using local resources, the composition and fermentation period may vary accordingly. The detailed nutrient content of the formulation is enumerated in Table 18.2. Studies report that the

TABLE 18.2 The plant nutrient content of different traditional liquid formulations.

Name of the formulation	Nutrient content (PPM)	References
Panchagavya	N (14000), P (800), K (5000)	(Ali, Ghatak, and Ragul, 2011)
Amritpani	N (440), P (110), K (340), Fe (3.7), Zn (0.7), Cu (0.1), Mn (01.1)	(Bhowate et al., 2023)
Sanjivak	N (14800), P (2800), K (3200)	(Vala and Chavda, 2021)
Kunapajala	N (700-3400), P (100-600), K (100-300)	(Mukherjee et al., 2023)
Jeevamrit	N (40-600), P (4-100), K (200-1000), S (300-400)	(Aulakh et al., 2013)
Beejamrit	N (1600), P (1200), K (5900), Fe (10), Mn (3), Cu (0.4), Zn (0.5)	(Singh et al., 2023)

The references are cited in Table 2.

recommendation of 4% *Panchagavya* spray has significantly improved yield attributes of black gram (Choudhary *et al.*, 2017), while 3% *Panchagavya* performs better in capsicum, green gram, and mustard (Ali, Ghatak, and Ragul, 2011).

18.4.3.2.2 Shasyagavya *Shasyagavya* is exclusively a 10-day decomposed formulation of vegetable waste and prepared using cow dung, cow urine, vegetable or crop waste, and water in 1:1:1:2 ratios (Ali, Chakraborty, and Paramanik, 2012). Recently, *Shasyagavya* has been reported to increase the yield and different yield attributes in *Kharif* transplanted rice (Biswas, Kumari, and Thakur, 2023). A 10% solution of *Shasyagavya* has significantly improved the yield parameters and the other quality attributes of French beans (Mahto and Dutta, 2018). However, there is no scientific report to date on the nutrient composition and content of *Shasyagavya*.

18.4.3.2.3 Amritpani This traditional formulation is prepared from 10 kg of cow dung, 250 g ghee, 500 g honey or jaggery. All the ingredients are mixed thoroughly and diluted with 200 L water for fermentation up to 7 days (Garg, Ram, and Priti, 2017). *Amritpani* is a source of primary macronutrients and provides other plant micronutrients required for plant growth (Table 18.2) (Bhowate *et al.*, 2023). Being a bio-enhancer, 3 to 5% solution of *Amritpani* improves fruits per plant and contributes to the equivalent yield in brinjal (Mohan, 2008).

18.4.3.2.4 Sanjivak *Sanjivak* is a concoction prepared from cow dung (100 kg), cow urine (100 L), jaggery (500 g), and water (300 L) and fermented for a period of 10 days. The nutrient content of the formulation is listed in Table 18.2. Field application of *Sanjivak* demonstrated improved growth and yield attributes in finger millets (Chavadi *et al.*, 2021) and groundnut (Mathukia *et al.*, 2023; Shekh *et al.*, 2018).

18.4.3.2.5 Kunapajala *Kunapajala* is the oldest known liquid manure prepared using cattle excreta and animal waste. Mukherjee *et al.* (2023) described the detailed composition of this formulation. This formulation is an excellent source of plant macronutrients (Table 18.2), plant growth-promoting bacteria, and plant hormones (Mukherjee *et al.*, 2023). Due to the multidimensional impact of *Kunapajala,* it has been widely recommended in rice (Mishra, 2007), black gram, mustard (Ali, Chakraborty, and Paramanik, 2012), tomato (Deshmukh, 2012), and okra (Kavya and Ushakumari, 2020).

18.4.3.2.6 Jeevamrit With the growing popularity of India's natural farming, *Jeevamrit* receives massive attention as an integral component in natural farming due to its multifaceted roles in agriculture (Kaur and Saini, 2021). Being a cattle excreta-derived formulation, it serves as a source of plant nutrients (Table 18.2) and microbes (Aulakh *et al.*, 2013). The preparation of *Jeevamrit* involves cow dung (10 kg), cow urine (10 L), jaggery (2 kg), pulse flour (2 kg), forest soil (1 kg), and water (200 L) (Sharma *et al.*, 2022). The plant growth-promoting effects of *Jeevamrit* have been reported in wheat (Bhadu *et al.*, 2021), summer pearl millet (Patel *et al.*, 2021), and marigold (Choudhary *et al.*, 2021). In addition, *Jeevamrit* also improves soil ecology and enhances nutrient availability and uptake from soil (Kaur *et al.*, 2020; Saharan *et al.*, 2023).

18.4.3.2.7 Beejamrit *Beejamrit* is commonly used as seed treatment and is prepared using cow dung (5 kg), cow urine (5 L), lime (50 g), forest soil, and water (20 L) (Bishnoi and Bhati, 2017). This microbe-based formulation is a rich source of plant growth-promoting bacteria and plant growth regulators (Mukherjee *et al.*, 2022). It also serves as a source of various macro- and micronutrients (Table 18.2). The earlier reports indicate that *Beejamrit* improves seedling survival

during an early stage and helps combat external stresses (Mukherjee *et al.*, 2022; Patel *et al.*, 2024). The earlier studies establish its role in the seed treatment as a carrier of beneficial microbe and a source of phytohormones.

18.5 Applications

18.5.1 Agricultural bio-inputs

In recent years, sustainable agriculture is gaining popularity as an alternate form of eco-friendly crop and livestock farming. The central theme of sustainable agriculture operates based on the circular bio-economy approach. This approach emphasizes resource conservation, recycling, and recovery from agricultural wastes and becomes an integral part of this system. In fact, several bio-inputs prepared from agro-food waste promote resource utilization sustainably. The waste-derived inputs recommended in agriculture are outlined below:

18.5.1.1 Bio-fertilizers

The intensive use of chemical fertilizers leads to environmental degradation (Peng *et al.*, 2023) that necessitates alternate nutrient cycles of crop growth. As discussed earlier, agricultural wastes are the source of several classes of plant nutrients and can be recycled back to agriculture employing extraction and recovery technologies. Agricultural wastes, including crop residues and animal excreta, can be used effectively as bio-fertilizers to improve crop growth and yield (Koul, Yakoob, and Shah, 2022). For instance, banana stem waste and poultry manure are nicely fit to prepare bio-fertilizers and act as carriers of plant-beneficial microbial inoculum (Riveracruz *et al.*, 2008). Hence, there is enormous potential for converting and recycling agricultural wastes into bio-fertilizers through appropriate methods.

18.5.1.2 Soil amendment

Soil amendments are the materials added to soil directly to improve its physico-chemical properties and biological entities (Maiti and Ahirwal, 2019). In particular, bio-fertilizers derived from organic waste can act as a soil conditioning agent to improve the physical structure of soils and enhance soil microbial activities (Wu *et al.*, 2020). Biochar, a pyrolysis-mediated product from organic waste, is also used for soil amendment purposes (Uras *et al.*, 2012). Even the incorporation of crop residues is known to improve soil biological as well as chemical properties of soil (Gaind and Nain, 2007). These studies indicate that several waste-converted bio-inputs can serve as soil amendments and play a crucial role in sustainable crop farming.

18.5.1.3 Bio-pesticides

Bio-pesticides broadly include bioactive compounds, natural molecules, microbes, and genetically engineered plants that confer resistance against pests (Sudakin, 2003). In this context, agricultural wastes can act as a source of natural and bioactive compounds, having pesticidal efficacy (Santana-Méridas, González-Coloma, and Sánchez-Vioque, 2012). For example, rice straw shows the natural insecticidal activity against mosquitoes (El-Maghraby *et al.*, 2012). Several studies have suggested that organic wastes, such as bio-oil, birch tar oil, pyroligneous acids, olive mill, wastewater, and grape pomace, can be used as a source of bio-pesticidal compounds (Šunjka and Mechora, 2022). In India, cow urine solely or in combination with other plant products is used traditionally as bio-pesticides and has shown its impact on reducing jassids, thrips, aphids (Patel *et al.*, 2019), fungal pathogens (Shridhar, Sharma, and Sharma, 2019), and psyllid (Mishra *et al.*, 2007).

18.5.1.4 Bioactive compounds

Bioactive compounds are well known for their anti-microbial, antioxidant, plant defense, and stress-responsive properties (Chalker-Scott and Fuchigami, 2018; Dincheva, Badjakov, and Galunska, 2023; S. Kumar *et al.*, 2020). Interestingly, agricultural byproducts are an important source of several bioactive compounds, such as phenolics, flavonoids, essential oils, xanthans, etc. (Santana-Méridas, González-Coloma, and Sánchez-Vioque, 2012). In support, formulations or composts derived from agro-wastes generally alleviate the protection of crop plants by combating external biotic and abiotic stresses.

18.5.1.5 Protein hydrolysates

Protein hydrolysates are the product of the enzymatic hydrolysis of proteins (Nasri, 2017), which have reported a biostimulative effect on crop health (Colla *et al.*, 2015). Agricultural wastes, specifically animal wastes, can be recycled into

smaller peptides as protein hydrolysates (Sun *et al.*, 2024). In support, studies showed that protein hydrolysates derived from animal residues have significantly improved the root structure and nutrient accumulation in maize (Santi *et al.*, 2017). Similarly, according to Paul *et al.* (2013), chicken feather hydrolysates induce better seed germination and seedling growth in Bengal gram. Additionally, protein hydrolysates have a clear positive impact on crop physiology and defense mechanisms (Malécange *et al.*, 2023). Notably, the application of protein hydrolysates has been gaining popularity recently in modern agriculture, and protein-rich agricultural wastes can serve as a source to recycle protein hydrolysates.

18.5.1.6 Plant bio-stimulants

Plant bio-stimulants are the substances, including microbes, required in a lesser amount and have a promising influence on plant growth, productivity, physiological responses, nutrient use efficiency, and abiotic stress tolerance (Calvo, Nelson, and Kloepper, 2014; Rouphael and Colla, 2020). Plant bio-stimulants include several bioactive compounds, micronutrients, protein hydrolysates, humic and fulvic acids, plant hormones, and plant growth-promoting microorganisms (Drobek, Frąc, and Cybulska, 2019). In principle, plant bio-stimulants are not a part of nutrient and pest management but focus on overall crop health improvement (Geelen, Xu, and Geelen, 2020). Agricultural wastes are sources of bioactive compounds, phytohormones, proteins, and free amino acids, and therefore, after proper transformation, recovery, and recycling, can be applied as plant bio-stimulants to improve crop growth and physiology (Puglia *et al.*, 2021).

18.5.2 Other value-added applications

Agricultural wastes could be a promising source of various value-added products. For instance, the utilization of agricultural waste for energy, fuel, and polymer production has been gaining more attention in recent years. Apart from these, agricultural waste as livestock feed is a part of the social system, thus promoting resource conservation and recycling of nutrients.

18.5.2.1 Green energy

The additive effects of global climate change and the shrinking of fossil fuel sources urgently necessitate renewable energy production (Meggyes and Nagy, 2012). Agricultural wastes can be transformed into various forms of green energy, such as bio-gas, thermal energy, triboelectricity, etc. (Sonu *et al.*, 2023). Bio-gas is a popular source of electricity and fuel for cooking. Bio-gas generated from lignocellulosic biomass of agricultural wastes, namely straw, bagasse, silage, vegetable peels, etc., has been an important innovation in modern times (Frankowski and Czekała, 2023). For example, India has the potential to generate 5000 million units of electricity annually from agricultural biomass (Tripathi *et al.*, 2016).

18.5.2.2 Bio-oil

Bio-oil is a nonconventional form of fuel that comprises alcohols, acids, aldehydes, ketones, esters, and phenols (Aparicio *et al.*, 2020). The concept of bio-oil turns out to be eco-sustainable and promotes waste utilization and valorization. In addition, it also emits less greenhouse gas than conventional fossil fuel burning (Demirbas, Pehlivan, and Altun, 2006). Agricultural crop residues are the low-cost alternate biomass sources for bio-oil transformation (Singh, Pant, and Krishania, 2023). Meanwhile, there are also attempts at bio-oil production from rice straw, tea oil shells (Y. Wang *et al.*, 2018), corn sticks, and palm leaves (Mohamed, 2018) through pyrolysis-mediated transformation.

18.5.2.3 Bio-sorbents

Biological substances generally used to remove pollutants from a solution are called bio-sorbents (Adewuyi, 2020). Agricultural wastes are applied to treat wastewater and soil to remove residual contaminants (Peng *et al.*, 2023). For instance, rice straw has been extensively used to remove metals from industrial effluent (Rocha *et al.*, 2009). There are also reports on green absorbents prepared from peanut and almond shells (Banerjee, Basu, and Das, 2019), corn cob (Luo *et al.*, 2018), and potato peels (El-Azazy *et al.*, 2019). Thus, from the ecological view, biomass utilization of agricultural wastes could be an innovative approach to removing contaminants from the environment.

18.5.2.4 Waste-derived catalysts

Agricultural wastes and wastewater are a source of low-cost, highly effective green catalysts (Chan *et al.*, 2011). Green catalysts, such as biochar and nanoparticles, derived from agricultural waste are used to degrade pollutants to treat wastewater (Kumar *et al.*, 2023). However, the transesterification reaction for bio-diesel production by homogenous

catalysts often faces difficulties and can be resolved by heterogeneous catalysts from agricultural waste (Khan *et al.*, 2021). These green catalysts can be utilized further to produce green hydrogen by water electrolysis (Chen *et al.*, 2023).

18.5.2.5 Livestock feed

Utilizing agricultural waste, specifically crop residues and food processing byproducts, as livestock feed is a common practice throughout the globe (Yafetto, Odamtten, and Wiafe-Kwagyan, 2023). Agricultural wastes, unprocessed or supplemented with additives, are commonly used as livestock feed (Koul, Yakoob, and Shah, 2022). The processing of agricultural wastes involves mechanical, chemical, and microbial treatment to transform them into edible forms to increase their nutritional value (Abou Hussein and Sawan, 2010; Yafetto, Odamtten, and Wiafe-Kwagyan, 2023). A balanced diet preparation based on agricultural wastes for animals is an important exercise. For instance, crop residues are rich in carbohydrates, although protein content is relatively low (Abou Hussein and Sawan, 2010). Therefore, microbial protein production technology using agricultural waste as protein-rich livestock feed could be an alternate supplement to animal diet (Rasool *et al.*, 2023).

18.5.2.6 Bio-polymers and natural fibers

Bio-polymers and natural fibers are gaining more attention since hazards linked to the manufacturing of synthetic plastic are scaling up (Maraveas, 2020). These bio-based polymers are produced from raw materials of agricultural wastes (Phiri *et al.*, 2023). In addition, bio-polymers are biodegradable and easily decomposed into biogases (Puglia *et al.*, 2021). There are successful efforts to produce bio-polymers using pineapple peel waste, grape pomace, orange peels, lemon peels, and rice husks (Maraveas, 2020; Vega-Castro *et al.*, 2016). Bio-polymers, on the other hand, intended for food packaging should improve quality based on rancidity, nutrient loss, and microbial growth, and, for this purpose, blueberry, grape seed, and green tea extracts will be particularly useful (Valdés *et al.*, 2014).

On the other hand, considering current supply and future demand, reusing agricultural wastes to produce natural fibers for the textile industry could be another eco-sustainable approach. The commonly used textile fibers require high cellulose content. Therefore, processing agricultural residues would be necessary to remove components like lignin and hemi-celluloses to fit in this industry. In this context, bagasse and corn husks would be reasonably better resources for producing natural fibers due to their high cellulose content (Koul, Yakoob, and Shah, 2022).

18.6 Challenges and barriers

18.6.1 Technical challenges

Nutrient extraction and recovery technologies often encounter technical challenges and are frequently associated with poor instrumentation facilities, environmental concerns, and nutrient loss during the operation. In these technologies, nutrient extraction, conversion efficiency, and further optimization of the method are critical stages to achieve overall success in waste management.

18.6.1.1 Efficiency of nutrient extraction

Techniques commonly used to extract nutrients from agricultural wastes face several technical challenges, and achieving nutrient extraction efficiency in quality and quantity is one of the biggest challenges. The membrane filtration technique used in nutrient removal from wastewater frequently experiences membrane fouling problems. Membrane fouling decreases the membrane performance and reduces its life span, and thus ultimately hampers the productivity of the technology (Xie *et al.*, 2016). On the other hand, high-intensity microwaves in the microwave-assisted method may degrade the bioactive compounds during extraction (Kala *et al.*, 2016). In solvent extraction techniques, the choice of solvent becomes critical due to its hazardous nature. In addition, residual solvents often result in degradation of target compounds (Amran *et al.*, 2021). Similarly, biological methods based on enzymes or microbial inoculants rely on favorable environmental conditions, specifically pH and temperature. Thus, achieving optimum conditions would be critical in extracting and recovering nutrients from agricultural wastes (Mehta *et al.*, 2015).

18.6.1.2 Nutrient loss during the recovery process

The main concern associated with almost all techniques is the frequent nutrient loss during the extraction. For example, composting is a well-known process of transforming agricultural wastes into soil amendments, and yet it suffers from nutrient loss during the transformation process. A study has reported a nutrient loss of 7 to 38% of N, 14 to 39% of P, and 1

to 38% of K during composting (Michel *et al.*, 2004). Similarly, the report on pyrolysis indicates that the conversion of plant nutrients during biochar formation is the biggest challenge (Wise *et al.*, 2012). On the other hand, according to Gil *et al.* (2019), maintaining optimal nutrient balance is crucial for anaerobic digestion to avoid excessive nutrient loss during the process. Therefore, nutrient loss is a common problem associated with these techniques, and unique challenges in each case make it further difficult to optimize the technology.

18.6.2 Economic and regulatory barriers

Nutrient extraction and recovery also encounter financial and regulatory challenges and require attention, particularly in developing nations. The following barriers seriously hinder the process of waste recycling and nutrient recovery.

18.6.2.1 Cost implications

In developing countries, cost involvement and drawing financial support are the biggest challenges in implementing technologies either in small-scale or industrial grade. The nutrient extraction techniques require facilities that initially increase the establishment cost of the process. The involvement of high operational cost is also an integral part of techniques, for example, solvent extraction, chemical precipitation, membrane filtration, ammonia stripping, and others. For example, membrane filtration involves a high energy cost to operate and increases the overall cost of the system indirectly (Mehta *et al.*, 2015).

18.6.2.2 Regulatory framework and standards

Utilization of agricultural waste to drive a resource-based circular economy still faces difficulties due to institutional regulations in many countries. The major challenge is related to the establishment of connections between authorities responsible for legislative policies. There is still a lack of well-defined appropriate policies, and in several cases, if policies are available, notable discrepancies hinder the overall implementation of those policies. Thus, to address these challenges, an integrated and holistic approach toward policy making and enforcement would be appropriate and necessary to promote sustainable recycling of agricultural waste (Kapoor *et al.*, 2020).

18.7 Conclusion and future perspectives

The SDGs of the UN have emerged as a regulatory framework to combat global environmental, economic, and political challenges. The second pillar of SDGs deals with the sustainability of ecology and the environment with a central focus on sustainable agriculture. Recycling of agricultural wastes is, in fact, one of the prime thirst areas that encourage sustainability of agriculture. Nutrient recovery from waste can meet several SDGs by improving sanitation, managing waste and resources, and restoring the ecology of the agroecosystem. Studies have also emphasized the importance of different methods for nutrient recovery from waste sources. With modifications of the current technologies based on instrumentation facilities and operational conditions, further optimization would help enhance nutrient recovery. Additionally, high-throughput multi-omics approaches to decipher microbial interaction for better nutrient recovery from waste could be a future alternative. Finally, the Life Cycle Assessment (LCA) of various products and processes from agricultural wastes can be employed to evaluate their environmental impact.

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Chapter 19

Transforming waste into worth: Exploring value-added products from agricultural waste

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Chapter Outline

19.1. Introduction 307
19.2. Agricultural contribution in food and environment 308
19.3. Sources and characteristics of agricultural waste 310
19.4. Management and utilization of agricultural waste 313
19.5. Strategies for conversion of waste to wealth 317
19.6. Agricultural waste generated value-added products in relation to SDGs 318
19.7. Future potential of bioconversion of agricultural waste using biotechnologies 321
19.8. Challenges and future research directions 324
19.9. Conclusions 325
References 325

19.1 Introduction

Waste management poses a significant difficulty for humanity in recent years. The combination of extensive industrial expansion, rapid population growth, and robust economic development has led to a significant increase in the production of waste. Based on data from the World Bank, the global yearly garbage generation is currently 2.01 billion metric tons and is projected to increase to 3.40 billion metric tons by 2050 (Kaza *et al.*, 2018). Traditionally, a substantial quantity of this waste is disposed of using methods such as incineration, chemical treatment, release into water bodies, or placement in landfills. Approximately 40% of the garbage that is produced is left untreated and dumped in open areas. The unregulated

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disposal of trash leads to significant pollution of the air, water, and soil, creating an environment conducive to the spread of diseases, thus impacting both the environment and human health (Tyagi and Kumar, 2020). These solutions are being extensively utilized worldwide due to their affordability and straightforward approach. Nevertheless, they have many drawbacks concerning waste treatment efficiency, which might result in significant harm to the environment. Disposing of waste by incineration or landfilling releases harmful greenhouse gases (GHG), which contribute to climate change and ultimately increase the planet's carbon footprint (Venil, Devi, and Ahmad, 2020). Due to technical improvements and the implementation of new policies centered on the waste to energy idea, there is currently a greater emphasis on investigating the renewable capabilities of various waste products.

Agro-industrial residues produced as a result of processing agricultural products in industries contribute significantly to worldwide trash creation. The solid and liquid waste that has undergone processing, such as pomace, peels, seeds, and byproduct streams, is abundant in biomass and contains numerous vital components, including proteins, carbohydrates, minerals, and so on. These waste materials have the potential to be used as a cost-effective source for producing valuable goods such as enzymes, pigments, bioactive chemicals, and biofuels. These products have a wide range of applications in industries and therapeutics (Panesar, Kaur, and Panesar, 2015; Venil, Devi, and Ahmad, 2020). In this particular situation, industrial biotechnology has proven to be more cost-effective and environmentally friendly than traditional methods, offering innovative technologies for the efficient utilization of waste materials. Techniques such as submerged and solid-state fermentation have been widely used to manufacture high-value products by using agro-industrial residue as substrates for biotransformation. Supercritical fluids, ultrasound, and microwave procedures are regarded as effective methods for extracting bioactive chemicals. In addition, advanced approaches such as recombinant techniques, metabolic engineering, co-culturing, and immobilized enzymes have improved the capacity for biotransformation and expanded the use of agro-industrial residuals. The extensive manufacturing of value-added goods not only contributes to the efficient use of waste and the mitigation of environmental issues but also establishes a foundation for bolstering the bio-economy in attaining sustainable development goals. This chapter thoroughly summarizes the present state and future potential of transforming agro-industrial waste into wealth resources in a sustainable manner through cutting-edge technologies with special emphasis on agro-byproducts and their different ways of utilization with innovative-end user products.

19.2 Agricultural contribution in food and environment

Abundant food supply is vital for social stability and human advancement, and yet also poses environmental concerns. Pesticides, fertilizers, and land conversion cause pollution, biodiversity loss, and ecosystem damage. By 2050, worldwide agricultural production may quadruple due to changing diets and population growth, potentially causing significant environmental harm. Agriculture is vital to food security, which affects all nations. Highly productive crops are essential for stable societies, especially contemporary ones. Societies also depend on ecosystems for essential services, including clean water production, waste decomposition, soil fertility, greenhouse gas mitigation, flood control, and the support of biodiversity that provides food, pollination, timber, fiber, medicines, and overall ecosystem functioning (Daily *et al.*, 2009).

Pingali, Ricketts, and Sahn (2015) suggest a three-step typology for agri-food systems that reflects structural transformation and the need for tailored approaches to improve diet quality and nutrition.

- In low-productive systems (e.g., sub-Saharan Africa), yield enhancement, variety, and gender equality are crucial.
- Modernizing systems (e.g., Asia) should diversify from staples to legumes and micronutrient-rich foods.
- Commercialized systems (e.g., Europe, North America) need to regulate ultra-processed foods and reduce sugar and salt intake among consumers.
- The Global Nutrition Report (Haddad *et al.*, 2015) delineates five evolutionary stages of food systems:
- Rural food systems: Characterized by low agricultural productivity and high staple reliance (e.g., Bangladesh, Ethiopia).
- Emerging food systems: More urbanized yet still staple-dependent (e.g., Pakistan, Thailand).
- Transitioning food systems: Countries like Brazil and Malaysia are examples.
- Mixed food systems: Exhibit moderate productivity and urbanization with low staple dependence (e.g., Germany, Italy).
- Industrial food systems: Highly urbanized with minimal staple reliance (e.g., United States, Sweden).

The 20th century saw a population boom due to improved sanitation and medicine. Projections suggest a rise from 7.3 billion in 2015 to 9.6 billion by 2050, peaking at 10.9 billion by 2100 (FAO, 2017). By 2050, global food demand is expected to double, with 70% due to dietary shifts and 30% to population growth (Tilman *et al.*, 2011). Current farming practices pose environmental risks, contributing to over 25% of global greenhouse gas emissions. Excessive use of nitrogen and phosphorus fertilizers surpasses natural ecosystems, impacting biodiversity and ecosystems (Smith, McTaggart,

and Tsuruta, 1997). Persistent agricultural chemicals contaminate ecosystems, affecting ecological and human health (Relyea, 2005). Severe soil degradation in developing countries is critical and reduces agricultural productivity.

19.2.1 Agriculture production and global population

Agriculture, despite its small global economic share, is vital to many, with 1.3 billion people engaged in farming in 2012. It constituted 2.8% of global income, including hunting, fishing, and forestry. Crop production demand is rising due to population growth, increased affluence, and biofuel consumption. By 2050, agricultural production may need to increase by 60 to 110% to feed the 870 million people chronically undernourished (WFP and IFAD, 2012). Boosting crop yields, not land clearing, is a sustainable solution for food security and poverty reduction, as most undernourished people are farmers (Brisson *et al.*, 2010). Advanced farming methods emphasize sustainable intensification to meet future food demands.

19.2.2 Advanced technology in agriculture production

Historically, technology has increased agricultural production amid resource limitations. Yet, rising population and climate change disrupt food supply-demand balance. With a projected 25% population increase to 9 billion by 2050, food production must double, necessitating substantial grain and meat production growth. New technologies in agriculture and best management practices promise enhanced production and sustainability. Foster and Rosenzweig (2010) note that technology availability, affordability, and farmers' profitability expectations drive agricultural technology adoption, while limited cultivable land is a significant constraint. Sustained adoption, profitability, and changing product prices are key to agricultural technology adoption. According to the Food and Agriculture Organization, global food production needs to increase by 70% by 2050 to meet the demands of a growing population. Several advanced technologies are used for increased production, problem detection, crop health monitoring, yield prediction, and optimizing resource usage (Uzhinskiy, 2023).

- **Genetic Advancements:** Breakthroughs in reproductive biology and inheritance mechanisms have empowered targeted modifications in crop traits, enhancing yield, mitigating environmental constraints, and surmounting production challenges. Genetic manipulation, through selective breeding or direct molecular techniques, is pivotal in augmenting productivity and tailoring crops to regional needs. (Sassenrath *et al.*, 2008).
- **Genetic Engineering:** Genetic engineering involves the deliberate modification genetic material of an organism's genetic material to introduce desirable traits. Techniques such as CRISPR-Cas9 and gene editing enable precise modifications. CRISPR technology, in particular, revolutionizes genome editing, enhancing accuracy and enabling the development of resilient and nutrient-enriched crops (Clercq, Vats, and Biel, 2018).
- **Crop Sensors:** Emerging crop sensors promise precision in fertilizer application, optimizing uptake while curbing leaching and groundwater runoff. These sensors enable real-time assessment of crop needs, elevating variable rate technology to new heights. Optical sensors gauge fertilizer requirements based on reflected light intensity, ensuring targeted application and minimal waste (Rehman *et al.*, 2016).
- **Advanced Machinery:** Recent advancements have endowed modern tractors with autonomous driving capabilities that ensure precise control, minimizing overlap and errors by navigating with sub-inch precision. They execute turns without human intervention, notably enhancing accuracy in pesticide application and weed management (Khan *et al.*, 2021). A proliferation of fully autonomous tractors is expected in coming years, heralding a transformative era in agricultural automation.

19.2.3 Impact of agricultural advancement in environment ecology

Agriculture extends beyond crop production, significantly impacting crucial ecosystem services vital for environmental health. These practices influence water quality, pollination, nutrient cycling, soil retention, carbon sequestration, and biodiversity conservation. Conversely, ecosystem services play a pivotal role in agricultural productivity. The interplay between agriculture and ecosystem services is evident in three main ways: (1) agricultural ecosystems yield valuable services like soil retention, food production, and aesthetic value; (2) they receive beneficial services from other ecosystems, such as pollination from non-agricultural environments; and (3) agricultural practices may affect ecosystem services provided by non-agricultural systems (Dale and Polasky, 2007). Despite productivity gains, increased agricultural activity has led to environmental impacts and reduced efficiency (Hazell and Wood, 2008).

19.2.3.1 Soil health

Agricultural intensification exacerbates and diminishes soil fertility, posing a significant risk to long-term crop productivity through soil degradation and water scarcity (Gomiero, Pimentel, and Paoletti, 2011). Accelerated erosion rates are altering carbon, nitrogen, and phosphorus biogeochemical cycles (Quinton *et al.*, 2010), with soil resilience to erosion closely

linked to organic matter and vegetation cover. Soil organic matter (SOM), predominantly found in the topsoil (Bot and Benites, 2005), comprises decomposing organic materials and significantly influences soil fertility. Fertile agricultural soils typically harbor substantial organic matter, but conventional agricultural practices that leave soil exposed for extended periods contribute to topsoil erosion and diminished SOM levels. Inadequately executed intensive agriculture poses a dual threat to soil ecology: it accelerates the oxidation and depletion of SOM while also predisposing soil to heightened erosion, necessitating the obligatory application of nitrogen fertilizers (Lal, 2004).

19.2.3.2 Biodiversity

The proliferation of agriculture directly impacts local biodiversity through landscape modifications, resulting in the displacement of indigenous communities and the depletion of ecosystem services (Gomiero, Pimentel, and Paoletti, 2011). The degradation of native habitats and the intensification of agricultural practices, characterized by the substitution of traditional seed varieties with genetically homogeneous, high-yielding crops, pose significant global biodiversity threats (Sachs *et al.*, 2009). Moreover, industrialized agriculture exacerbates the decline in crop biodiversity, leading to the loss of numerous agricultural species and cultivars (Jackson *et al.*, 2005). This expansion of agriculture imperils the vital ecosystem services provided by biodiversity, notably pest control (Crowder *et al.*, 2010). Additionally, alterations in land use contribute to escalating CO_2 levels and modifications in global river runoff patterns. Furthermore, the intensification of agriculture and the utilization of agrochemicals diminish the vital contributions of pollinators, particularly bees, essential for pollinating 35% of global crop production. This underscores the urgent necessity to address these challenges to ensure the sustainability of agricultural productivity and ecosystem well-being (Pimentel and Burgess, 2014).

19.2.3.3 Climate change

Climate change stands out as a prominent challenge within sustainable development objectives, particularly concerning sustainable agriculture. It encompasses alterations in climate patterns over time, stemming from both natural fluctuations and human-induced activities (Vardy *et al.*, 2017). Its ramifications are vast, with agriculture emerging as one of the sectors most profoundly affected. Agriculture, vital for livelihoods, food security, and economic stability, faces profound impacts from climate change. Agriculture contributes significantly to greenhouse gas (GHG) emissions, primarily through the release of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). CO_2 emissions largely result from microbial decomposition or the burning of plant residues and soil organic matter (Smith *et al.*, 1997), while N_2O emissions predominantly stem from nitrogen fertilizers (Teira, 2010). Despite their relatively lower atmospheric concentrations compared to CO_2, CH_4 and N_2O exhibit significantly higher global warming potential (GWP), with CH_4 being 23 times and N_2O being 296 times more impactful than CO_2 (Garnett, 2008). The agricultural sector, inclusive of land-use changes like deforestation driven by expansion for food, fiber, and fuel production, accounts for approximately 30% of total GHG emissions. Moreover, the extensive supply chain of agricultural products, coupled with post-purchase waste generation by consumers, further contributes to GHG emissions.

19.3 Sources and characteristics of agricultural waste

The residues remaining after cultivating crops and/or during the initial processing of raw agricultural products, such as fruits, vegetables, dairy products, meat, poultry, and other items, are referred to as agricultural wastes or agro-wastes. Approximately 30% of the global agricultural output is ultimately disposed of as agro-waste (El-Ramady *et al.*, 2022). Waste materials are disposed of and thrown away since they are no longer usable. Agro-industry and agriculture produce around two-thirds of all organic waste produced in many industrialized nations. Agricultural wastes consist primarily of organic substances and may be solid, sediment, or liquid (Weiland, 2008). They may be produced as raw materials, byproducts, or final goods as a result of various agricultural activities, such as horticultural, seed growing, dairy farming, livestock breeding, grazing, nursery plots, market gardens, forestry, or woodland production (El-Ramady *et al.*, 2022); for instance, they may be generated subsequent to the harvest of the primary crop (straw in cereal production) or subsequent to the processing of the product in industrial operations (bagasse, pulp, oil cakes); if the products fail to meet the market's quality standards (fruits and vegetables that are rejected); if the plant products are unable to be sold at the appropriate time (products that are overlapping) (Weiland, 2008).

19.3.1 Categories of agricultural waste

19.3.1.1 Cereal crops waste

Cereals are among the most important dietary sources and crops in the human diet. Throughout the cereals processing chain, massive amounts of lignocellulosic biomass—a type of agricultural waste—are produced. Approximately 12.9% of total food waste is generated during the processing and manufacture of cereal, and around 30% of the weight of cereal is

lost or squandered. Depending on the type of cereal and on the process applied, cereal waste byproducts are generated in different technological steps: straw and cob are the wastes produced during the cleaning grain process, bran is generated when the cereal is used for the extraction of some compounds, such as corn and rice oil, or when the grains are polished during the rice processing. Parboiling rice results in a significant quantity of waste that can be utilized as a biofuel. Similarly, the beer industry produces brewery spent grain (BSG), which is a waste material containing phenolic chemicals that possess antioxidant and antimicrobial characteristics. Wheat bran, wheat germ, rice bran, rice germ, corn germ, corn bran, barley bran, and brewery spent grain (BSG), stover, husk, and skins from maize, and stover from millet are examples of wastes produced from major cereal crops (Fărcaș *et al.*, 2022).

19.3.1.2 Horticultural waste

The primary causes of horticultural waste include farming operations within horticulture production systems, chemical wastes during cultivation, discarded food waste, and kitchen trash.

19.3.1.2.1 Waste from farming activity. Waste from farming operations may be produced in the largest proportions. Many intercultural operations, including training, pruning, thinning, earthing up, and so on, are required for the entire process and produce wastes such as leaf residues, debris, and dead leaves. Many farming practices generate a large amount of waste in agriculture. One of the most popular cultivation systems in horticulture is the greenhouse (Koukounaras, 2021). Greenhouses generate 39,215 tons of waste out of a total of 90,738 tons; this accounts for 43% of the overall waste. With the second-highest waste getting a rate of 23%, disinfection is another method of collecting waste. The constant application of herbicides, insecticides, and pesticides during cultivation produces wastes. These are mostly solid trash, including bottles, pesticide containers, etc. (Hassan *et al.*, 2022).

19.3.1.2.2 Wastes from horticultural foods. The kitchen wastes in our home are primarily composed of horticultural foods like fruits and vegetables. Examples of biowaste from horticulture foods include potato peels, onion waste, papaya peels, mango peels and seeds, citrus peels and seeds, pomegranate peels and seeds, and tomato peels (Hassan *et al.*, 2022).

19.3.1.3 Pulse and legume waste

At 44%, legumes are the largest contributor to food waste, followed by root vegetables and tubers (20%) and grains (19%). The peel of black gram (*Vigna mungo* L.), the unutilized parts like stems/stalks, the hulls and leaves of pigeon pea (*Cajanus cajan* Millsp.), pea (*Pisum sativum*) pods, peanut (Arachis hypogea) shells, residual straw of soybean (*Glycine max*), and faba bean (*Vicia faba* L.) straws are considered legume waste (Ankita *et al.*, 2023).

19.3.1.4 Post-harvest and processing waste

Sorting, storing, processing, packing, shipping, marketing, distributing, and human consumption are some of the processes that might result in post-harvest waste. The main factors contributing to the trash generated during this stage are incorrect handling, insufficient harvesting equipment, unskilled personnel, and a lack of laws and rules for the management of post-harvest waste (Mohanty, Mankoti, and Meena, 2023). One byproduct of rice processing, for instance, is rice bran, which contributes significantly to annual food waste. When water is extracted from sugarcane stalks, a fibrous residue known as sugarcane bagasse comes out over (Sadeghi *et al.*, 2023). Food waste is produced in large quantities as a result of food production, processing, and preparation. Different types of food processing industries wastes are: (1) waste from the fermentation industry, (2) fruit and vegetable industry waste, (3) waste from the sugar and starch industry, (4) dairy industry waste, (5) meat processing industry waste, (6) coffee industry waste, (7) palm oil industry waste, and (8) fish processing industry waste (Raj *et al.*, 2016).

19.3.2 Chemical characterization of agricultural waste

19.3.2.1 Composition of agricultural wastes

Agricultural waste is categorized as lignocellulosic biomass, which is made up of complex molecules like cellulose, hemicellulose, lignin, ash, and a few extractives, mostly protein. In degradation, components' structures are broken down into simple monomers so that they can be changed into various configurations. The majority of agricultural wastes include a higher percentage of cellulose than hemicellulose or lignin combined. The hemicellulose concentration of biomass greatly influences its capacity to be turned into biofuel. Plants require lignin, which is second only to cellulose in importance. On a dry basis, the majority of crop residues and agricultural wastes are made up of 35 to 50% cellulose, 20 to 35% hemicellulose, 15 to 20% lignin, and 15 to 20% extractives (ash, protein, etc.) (Omojola Awogbemi and Kallon, 2022). Table 19.1 presents the chemical composition of agricultural wastes.

TABLE 19.1 Lignocellulosic compositions and proximate composition analysis of agricultural wastes.

Agricultural waste	Lignocellulosic compositions			Proximate analysis (% w/w)			Composition analysis (% w/w)					References
Cellulose	Hemicellulose	Lignin	Moisture	Ash	Volatiles	C	H	N	S	O		
Rice husk	33.40–50.10	3.80 –21.70	6.80 –20.40	–	16.7	67.5	36.52	4.82	0.86	–	41.1	(Suhail *et al.*, 2022; Boonpoke *et al.*, 2011)
Rice straw	39.2	23.5	36.1	14.17	14.93	66.33	40.79	7.66	1.17	0.49	49.89	(El-Tayeb *et al.*, 2012; Ai *et al.*, 2013)
Wheat straw	32.9	23.5	36.1	3.3	3.23	–	46.5	6.3	0.9	–	46.3	(Singh Nee Nigam,Gupta, and Anthwal, 2009; Zanzi *et al.*, 2001)
Corn	61.2	19.3	6.9	4.3	0.9	78.7	46.8	6	0.9	–	46.3	(El-Tayeb *et al.*, 2012; Tsai *et al.*, 2001)
Almond shell	32.5	25.5	24.8	10	0.6	80.3	50.5	6.6	0.2	0.01	42.69	(González *et al.*, 2009)
Sugarcane bagasse	42.16	36	19.3	6.2	0.9	–	47.3	6.2	0.3	–	46.2	(Chen *et al.*, 2012; Zanzi *et al.*, 2001)
Palm shell	29	47.7	53.4	7.96	1.1	72.47	50.01	6.9	1.9	0	41	(Adinata, Wan Daud, and Aroua, 2007)
Coconut shell	19.8	68.7	30.1	8.21	0.1	73.09	48.63	6.51	0.14	0.08	44.64	(Daud and Ali, 2004)
Walnut shell	40.1	20.7	18.2	11	1.3	71.8	45.1	6	0.3	0	48.6	(González *et al.*, 2009)
Olive stone	14	15	42	10.4	1.4	74.4	44.8	6	0.1	0.01	49.09	(Cagnon *et al.*, 2009; González *et al.*, 2009)
Banana empty fruit bunch	8.3	21.23	19.06	5.21	15.73	78.83	41.75	5.1	1.23	0.18	51.73	(Sugumaran *et al.*, 2012)
Pomegranate seed	26.98	25.52	39.67	5.38	1.83	78.71	49.65	7.54	4.03	0.65	38.13	(Uçar *et al.*, 2009)
Almond tree pruning	33.7	20.1	25	10.6	1.2	72.2	51.3	6.5	0.8	0.04	41.36	(González *et al.*, 2009)

19.4 Management and utilization of agricultural waste

19.4.1 Management options for agricultural waste

Agricultural wastes are often produced from several sources, namely crop, livestock, and aquaculture. Based on a recent assessment, the global annual output of agricultural waste amounts to around 1 billion tons (Sathish Kumar, Sasikumar, and Dhilipkumar, 2024). The potential toxicity of agricultural residue extends to plants, animals, and humans via numerous direct and indirect pathways. Waste management is the process of collecting, transporting, disposing, recycling, and monitoring garbage. In food waste management, prevention is the primary option, while reuse and recycling are secondary. The amount of waste produced is reliant on the specific farming practices used. Agricultural waste comprises crop remnants, green plant parts, pesticide containers, manufacturing and supply chain packaging, excessive chemical fertilizer, fisheries feed waste, manure, and slaughterhouse organics. Most agricultural waste is burned or dumped in landfills without treatment, which can increase greenhouse gas emissions and harm the environment and economy. Wastes must be regarded as potential resources rather than undesirable to prevent the spread of hazardous materials and contamination.

The biodegradability and nutritional richness of agricultural waste make it an asset with tremendous potential with proper management. One of the earliest biomass conversion processes is burning agricultural waste for fuel. Traditional waste management practices, such as landfilling, open dumping, burning, or incineration, are criticized for increasing carbon footprints. Composting and anaerobic digestion are two examples of more conventional waste management methods. Food waste valorization emerges as a promising substitute when efforts at prevention and reduction have failed. Nutrient loss, decreased soil fertility, combustion-induced emissions of methane and nitrous oxide, and other problems are all potential outcomes of improperly managing agricultural waste. Nearly 21 to 37% of greenhouse gas emissions are attributed to agricultural activities (Boomi *et al.*, 2019). Biogas production has emerged as a highly effective waste management method. However, new opportunities for managing agricultural waste have emerged as a result of developments in waste-to-energy technology. Pyrolysis and hydro-gasification are very effective technical processes for converting agricultural waste into chemicals. Plasma gasification produces electricity from waste. A new technology termed microbial fuel cells has been developed that utilizes waste as fuel for the generation of electricity (Rojas-Flores, 2022).

19.4.2 Transforming agricultural waste into value-added products

In recent times, technological progress has created fresh opportunities for the sustainable handling of agricultural waste and the promotion of economic growth. It is possible to create value-added goods from agricultural waste due to its high organic content. Waste may be utilized as substrates and raw materials to create novel value-added goods (Babu *et al.*, 2022). Producing biofuels, enzymes, biopolymers, biochemical, and countless other compounds from food industry waste is possible since this waste is rich in complex proteins, lipids, and carbohydrates. Many valuable items have been developed via the exploitation of waste materials. For example, gas-permeable packaging films made from peanut shells can extend the shelf life of food products, hydrogen can be produced from sunflower husk and bagasse, collagen, gelatin, chitin, and chitosan from marine waste, keratin and biogas from poultry waste, bioplastic from industrial black liquor, recycling cellulosic fibers from cotton waste, electrode materials, and natural polymers can be obtained from biomass waste. The bioactive substances in agricultural wastes are valuable resources for making biofuels, enzymes, vitamins, antioxidants, animal feed, antibiotics, and chemicals. One of the most important applications of microbial biotechnology and nanotechnology is the bioconversion of agricultural waste into bioactive chemicals used in pharmaceuticals and food (Figure 19.1).

19.4.2.1 Food/Feed ingredients

Agricultural byproducts of crops, such as wheat bran, rice bran, soy pulp, peanut meal, molasses, palm oil mill effluent, palm kernel cake, and olive oil byproducts, can be incorporated into aquafeed formulations due to their high nutritional value and cost-effectiveness. It is feasible to produce large quantities of superior natural cellulose fiber by using the lignocellulose found in maize, wheat, rice, sorghum, pineapple, and banana leaves. As a sweetener and a source of calcium and iron, molasses is a great nutritional supplement for animals. Among its many uses, molasses lends itself to the production of vinegar, alcohol, and other drinks. Animal-derived gelatin encounters use limitations as a result of religious customs. However, widely acceptable gelatin and collagen are manufactured from fish skin and bone from fishery processing byproducts. Fish bones have a high calcium content. It is feasible to get bio calcium powder in large quantities from the bones of precooked tuna, which is a byproduct of the fishing business.

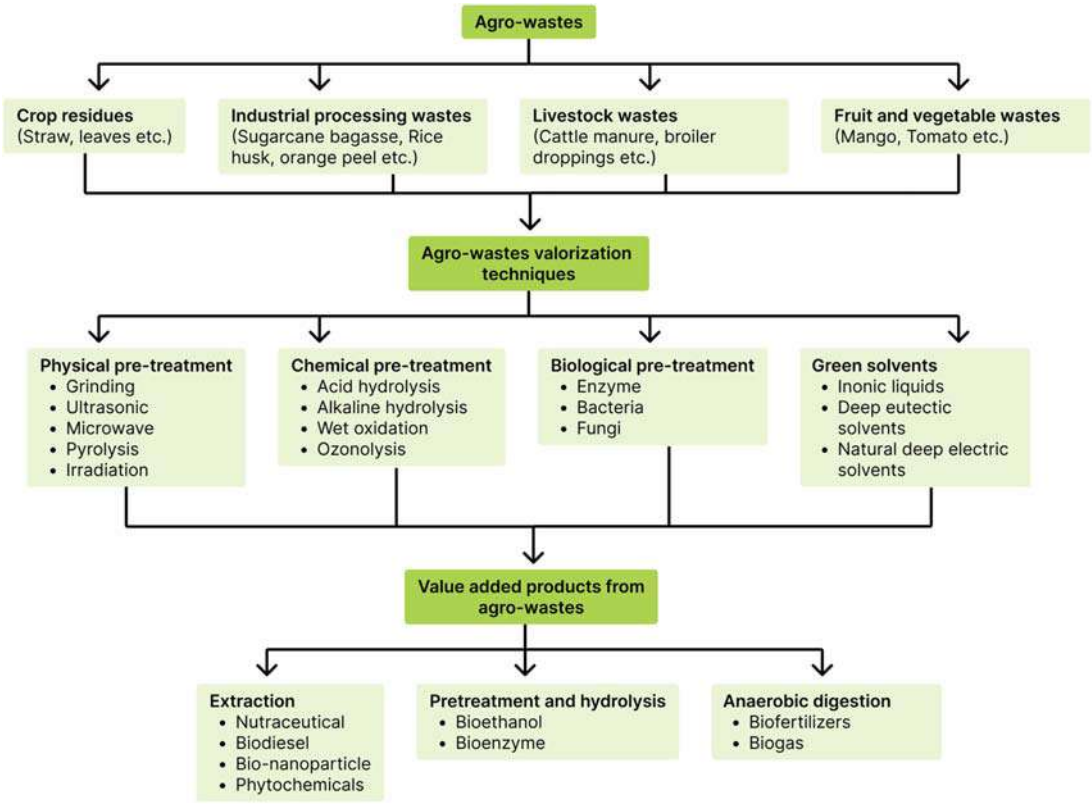


FIGURE 19.1 **Exploring agro-waste sources: techniques for valorization and production of value-added products.**

Plant cell walls mostly consist of polysaccharides, proteins, and lignin, with small amounts of phenols and acetyl groups. Alkaline-acid-extracted protein from rice burn is a suitable alternative to albumin and gluten-free-based products for quality improvement by enriching with proteins (Rawdkuen and Ketnawa, 2020). Agro-waste has several important constituents such as proteins, enzymes, dietary fibers, fatty acids, bioactive compounds, flavors, and aromas. These components have been used in the pharmaceutical, food, and cosmetic sectors (Babu *et al.*, 2022).

19.4.2.2 Energy generation

Population growth has caused energy and solid-waste crises, causing environmental degradation. Agricultural waste is an abundant source of renewable energy. Wastes from agricultural systems can be converted into electricity through a series of energy transformations. Plasma gasification results in the generation of electricity from waste. An agricultural biogas plant generates heat and power from manure, slurry, and other agricultural waste. Microbial fuel cells are a novel energy source that may be used to generate power from fruit byproducts (Rojas-Flores, 2022). Wastewater from many sources, such as palm oil mills, mustard and tuber molasses, breweries, and wineries, may be used by microbial fuel cell technology to generate energy. The two most promising ways to transform agricultural byproducts into energy are gasification and liquefication. Biodiesel and bioethanol are two examples of biofuels that may be produced from biomass feedstocks like sugarcane, corn, beetroot, sunflower, corn, soy, and palm. Major participants in the agricultural waste-to-energy sector include Ameresco, American Renewables, LLC, Bio Catalytics, Fulcrum Bio Energy, Clean Power, Cleanergen Corporation Elemental Energy, BioCaldo, and Enel Green Power. In the future, farmers cooperatives and industrial fruit companies will be able to use their waste to produce electricity for their own consumption.

19.4.2.3 Carbon source for microbes

Agricultural waste is a rich and promising cost-effective resource for generating renewable energy. Bacterial cellulose, a biopolymer, has gained importance in the recent past due to its physicochemical properties. As an inexpensive carbon source for bacterial cellulose, agricultural wastes such maize stalks, coffee cherry husks, mango pulp, citrus peels, potato

peels, banana peels, pineapple, orange peels, and date fruit waste might be made useful. Banana stalks, loofah sponges, sorghum stalks, sweet potato stalks, watermelon skins, and wheat husks release carbon well for biological denitrification or nitrogen removal from wastewater (Gao *et al.*, 2022). As a carbon source, lignocellulosic biomass such as sludge, food waste, Municipal solid waste (MSW), and paper mill effluents has been used in anaerobic fermentation to generate short-chain fatty acids (Tomás-Pejó *et al.*, 2023).

19.4.2.4 Bio-fertilizer

The majority of organic waste and byproducts from animal manure, agricultural, and food processing industries meet the essential criteria to be used as bio-fertilizers. Producing bio-fertilizers from waste is an effective method for recycling organic material. Compost from waste becomes nutrient-rich organic fertilizer, enhancing soil health and lowering chemical fertilizer consumption. Utilizing wheat husk, composted bovine dung, and corn cob, a cost-effective bio-fertilizer was manufactured that dissolves phosphates (Wang *et al.*, 2015). Olive milling waste is composted to provide a good fertilizer with low water-soluble organic matter, phenolic, and lipidic components. Composting poultry slaughterhouse waste produces bio-fertilizers with 60% yield improvement in certain crops and free-form phytotoxicity. Solid-state fermentation bio-fertilizers from watermelon, papaya, and banana are promising fertilizers with high pH and potassium content for growing plants (Lim and Matu, 2015). Animal feather biomass is a significant source of N and might be used as bio-fertilizers in the agroindustry to reduce inorganic fertilizer use (Gupta *et al.*, 2023).

19.4.2.5 Chemicals and fuels

These days, there is state-of-the-art technology that can turn trash into chemicals and fuel in an effective and environmentally responsible way. Pyrolysis and hydro-gasification are powerful ways to make compounds from agricultural waste. A variety of valuable byproducts may be extracted from agricultural waste, including fuel alcohol, fertilizer ammonia, feed glucose, oil, char, and low-heating gas (Feng *et al.*, 2024). They can replace fossil fuels in vehicles and other machinery while also reducing pollution. Biomass is partially oxidized during gasification to produce syngas, a gas mixture. In addition to producing electricity, syngas has other potential uses in the chemical and liquid fuel industries. In underdeveloped nations, biogas generation is an efficient waste management approach. Anaerobic digestion of crop residues converts organic wastes into methane and other combustible gases. Enzymatic hydrolysis and fermentation of starch-based agro-wastes produce bioethanol worldwide (Panpatte and Jhala, 2019). Lignin from agricultural waste may be used to synthesize phenols, vanillin, aromatic diacids, quinones, cyclo hexanes, and olefins. Combining photo- and dark fermentation to produce biohydrogen from rice and wheat straw is a clean technology. A two-step fermentation process called acetone−butanol−ethanol may create biobutanol from residual biomass, energy crops, and forestry waste (Zielińska and Bułkowska, 2024).

19.4.2.6 Pigments

Human health-beneficial bioactive pigments are popular. Extraction of pigments from agricultural waste, including flavonoids, anthocyanins, astaxanthin, prodigiosin, canthaxanthin, betalains, lycopene, and β-carotene, has broad uses in food, medicines, textiles, cosmetics, and more. Fermentation may extract pigments from bacteria, fungi, and yeast. Microbial growth medium from agro-industry waste might provide low-cost pigments. Pigments may be produced via submerged and solid-state fermentation (SSF) using agro-industrial leftovers, which are ideal as nutritional supports for microbial development. Agro-processing firms create a lot of trash while processing fruits and vegetables. The peel of fruits and vegetables contains most of the pigments, which are removed during processing and discarded. Many researchers use proteolytic, lipolytic, and cellulolytic enzymes to maximize pigment recovery from processing waste (Ranveer *et al.*, 2023). Besides microbial mining, ultrasound, pulsed electric field, supercritical CO_2, pressured liquid extraction, microwave, and ohmic heating are some innovative methods for economically producing pigments from agricultural waste (Carrillo *et al.*, 2022). Cyaniding from apple peel, beta-carotene and lycopene from apple seed, carotenoid, beta-carotene, and phenolic pigment from orange peel, anthocyanins and carotenoids from mango peels, cherry pomace, and betalain from red beetroot root are important bioactive pigments from agricultural waste (Martins *et al.*, 2023). These pigments have applications in textile, pharmaceutical, food, cosmetics, bio-indicators, sensors, diagnostic devices, nano-optics, paints, polymers, and more.

19.4.2.7 Secondary metabolites

Bioactive chemicals are supplemental nutritional components found in food and plants in minute amounts in their native forms. Metabolites, including antibiotics, mycotoxins, alkaloids, food-grade pigments, plant growth stimulants, and

phenolic compounds, are the most frequent bioactive molecules. Secondary metabolites may be extracted from agricultural waste via fermentation, microwaving, ultrasonic assistance, subcritical water extraction, pressured liquid extraction, solvent extraction, and other methods. The secondary metabolites polyphenols and flavonoids are abundant in higher plants and have powerful antioxidant properties. Another possible source of antioxidant phytochemicals is solid byproducts from the wine business. The skins of fruits such as mangosteen, rambutan, and bananas are abundant in polyphenols (Azeez, Narayana, and Oberoi, 2017). Pulp from olive mills is a good source of biophenols, which have antibacterial, molluscicidal, and antioxidant properties. Solid byproducts from the wine industry are also a potential source of antioxidant phytochemicals; peels from bananas, rambutan, and mangosteen are rich in polyphenols (Table 19.2).

TABLE 19.2 Agro-wastes transformed into different useful products.

Agro-wastes	Microorganism	Use of single-cell protein	References
Brewery waste	*Pleurotus ostreatus*	As single-cell protein	(Wang, Sakoda, and Suzuki, 2001)
Cassava wastes	*Saccharomyces cerevisiae*	As single-cell protein	(Ubalua, 2007)
Coffee pulp, coffee husk	*Candida utilis*	As protein rich biomass	(Orozco *et al.*, 2008)
Defatted rice polishing	*Cryptococcus curvatus*	As single-cell protein, protein enriched biomass	(Rajoka *et al.*, 2006)
Beet molasses and corn gluten meal	*Microsphaeropsis spp; Streptomyces cyaneu*	As single-cell oil	(El-Fadaly, El-Naggar, and Marwan, 2009)
Wheat bran, straw, sugar beet pulp	*Phanerocheate chrysosporium*	As single-cell protein, food ingredients	(Orozco *et al.*, 2008)
Agro-byproduct	**Microorganism**	**Organic acid**	**References**
Apple pomace	*Aspergillus niger* NRRL 567	Citric acid	(Dhillon *et al.*, 2011)
Apple industry waste	*Rhizopus oryzae* 1526	Fumaric acid	(Das, Brar, and Verma, 2015)
Oil palm empty fruit bunch	*A. succinogenes* ATCC 55618	Succinic acid	(Akhtar and Idris, 2017)
Apple pomace	*Propionibacterium freudenreichii*	Propionic acid	(Piwowarek, Lipińska, and Hać-Szymańczuk, 2016)
Sugarcane molasses	*Aspergillus niger* ARNU-4	Gluconic acid	(Sharma, Vivekanand, and Singh, 2008)
Citrus peel	*Rhizopus oryzae*	Lactic acid	(Tay and Yang, 2002)
Agro-byproducts	**Microorganism**	**Enzyme**	**References**
Wheat bran	*Aspergillus foetidus*	Xylanase	(Chapla *et al.*, 2010)
Sugar beet waste	*Aspergillus heteromorrphus*	Laccase, manganese peroxidase	(Vassilev *et al.*, 2009)
Grape pomace	*Aspergillus awamari*	Pectinase	(Botella *et al.*, 2007)
Corn cob and oat	*Penicillium janthinellum*	Xylanase and pectinase	(Oliveira, Porto, and Tambourgi, 2006)
Banana peel	*Aspergillus niger* NCIM 616	Amylase	(Krishna, 2012)
Soybean hulls	*Aspergillus niger* NRRL3	Cellulase	(Julia *et al.*, 2016)
Waste bread pieces	*Aspergillus awamori*	Protease	(Melikoglu, Lin, and Webb, 2015)
Hazelnut shell	*Bacillus subtilis*	Pectinase	(Uzuner and Cekmecelioglu, 2015)
Agro-byproduct	**Microorganism**	**Flavor compounds**	**References**
Coffee husks	*Ceratocystis fimbriate*	Pineapple flavor acetaldehyde and 3-methylbutanol	(Soares *et al.*, 2000)
Cassava bagasse	*Kluveromyces marxianus*	Fruity aroma	(Medeiros *et al.*, 2001)

TABLE 19.2 Agro-wastes transformed into different useful products.—cont'd

Agro-byproduct	Microorganism	Flavor compounds	References
Semi-solid maize	*Pediococcus pentosaceus Lactobacillus acidophilus*	Dairy flavor compounds	(Escamilla-Hurtado *et al.*, 2005)
Pineapple cannery waste	*Aspergillus niger*	Vanillin	(Lun, Wai, and Ling, 2014)
Kitchen waste	*Xanthomonas campestris* LRELP-1	Xanthan gum	(Li *et al.*, 2016)
Food industry waste	*Rhodosporidium toruloides* DSM 24444	Wax esters	(Papadaki *et al.*, 2017)
Pineapple waste	*Chromobacterium violaceum* UTM5	Pigments	(Aruldass *et al.*, 2015)
Papaya peel	*Acetobacter aceti*	Vinegar	(Vikas and Mridul, 2014)
Agro-waste	**Microorganism**	**Biofuel**	**References**
Potato peel Waste paper/Kitchen waste	*Aspergillus niger, Saccharomyces cerevisiae*	Bioethanol	(Chintagunta, Jacob, and Banerjee, 2016) (Nishimura *et al.*, 2017)
Dairy waste Cheese whey wastewater	*Bacillus licheniformis*	Biohydrogen	(Srivastava *et al.*, 2017)
Food industry derived waste	*Candida lipolytica*	Biosurfactants	(Rufino, Sarubbo, and Campos-Takaki, 2007)
Food waste	*Geobacter Bacteroides*	Bioelectricity	(Jia *et al.*, 2013)
Fruit pomace/waste frying oil	*Pseudomonas resinovorans*	Biopolymer (medium-chain length polyhydroxyalkaonates)	(Follonier *et al.*, 2014)

19.5 Strategies for conversion of waste to wealth

The ongoing technological advancements in agriculture and agro-industries, coupled with population growth, have resulted in increased production and agricultural waste, highlighting the need for effective methods to transform this waste into sustainable, affordable, and eco-friendly products. Strategies for converting agricultural waste into value-added products can be classified into two categories: conventional and advanced approaches. Conventional approaches include methods such as briquetting, waste-to-energy conversion, enzymatic degradation, and adsorption. On the other hand, advanced approaches explore emerging opportunities in various fields including the production of nutraceuticals, development of packaging and flavoring agents, and the creation of waste-induced nanoparticles, etc. Both these approaches hold immense potential for effectively utilizing agricultural waste.

19.5.1 Conventional approach

Briquettes, compacted and bound fuel resources, are produced from food waste materials like vegetable and agro-waste through a process called briquetting. Briquetting, a key step in waste management and sustainable energy production, is globally recognized for its potential to mitigate environmental and health issues linked to traditional wood/coal burning (Srivastava *et al.*, 2014). Agro-waste and coal-agro-waste blend briquettes are noted for their high thermal efficiency. They are formed through the combustion of coal and biomass, with vegetable waste burning at lower temperatures, resulting in less smoke and more heat. The lignin in the waste enhances the calorific value and aids in particle binding for briquette formation. Binding agents such as paper, clay, or sawdust, when used with agro-waste, enhance combustion and calorific value.

Meanwhile, vegetable waste can be repurposed as animal feed, enhancing herbivore nutrition, instead of being discarded in landfills (Wadhwa, Bakshi, and Makkar, 2015). However, the presence of heavy metals in agro-waste necessitates effective pretreatment systems for safe and feasible use in animal feed. There is growing interest in converting waste into eco-friendly biofuels (Ganesh, Sridhar, and Vishali, 2022). Modifying process parameters and microbes can recover

biohydrogen. Mateus *et al.* (2020) used a two-stage digester to produce biogas and biohydrogen from fruit pulp waste, increasing energy production by 22.4%. It has also been stated that enzyme treatment, via solid-state fermentation (SSF) or submerged fermentation (SmF), offers distinct advantages. SSF processes water-insoluble material efficiently, while SmF synthesizes microbial metabolites from high-cost materials. Amylase and cellulase are popular enzymes for their capacity to convert β-glucose and produce biofuels efficiently (Deshmukh, Deshpande, and Tondon, 2010). Biofuels like ethanol and hydrogen, derived from agro-waste, could replace petroleum fuels, reducing greenhouse gas emissions. Using *Saccharomyces cerevisiae* for post-acid hydrolysis of fruit waste enhances conversion into fermented sugar and ethanol (Gosavi, Chaudhary, and Durve-Gupta, 2004). Despite cost concerns, co-culturing enzymes at specific ratios improves productivity and waste management.

Disposing waste in waterways harms marine life and humans. In this case, conventional adsorption techniques, such as activated carbon, clay, or silica, effectively treat wastewater but can be costly. However, bio-sorbents from fruit and vegetable waste present a natural, cost-effective alternative for wastewater treatment. Studies have evaluated the potential of various waste materials, such as carrot, potato, and mango peels, for contaminant removal. Factors like pH, temperature, and contact time affect the process, yielding promising kinetic curves. Activated carbon from banana peels and agricultural waste has been used to remove pollutants like PAHs and organic micropollutants. Dyes were effectively removed using activated carbon from banana and orange peels (Djilani *et al.*, 2012). Recent research explores the potential of bio-sorbents and magno-sorbents for contaminant removal (Aichour and Zaghouane-Boudiaf, 2020). Recycling and renewing adsorbents effectively treat heavy metal-loaded adsorbers cost-effectively, potentially aiding large-scale environmental remediation (Zhang *et al.*, 2020).

19.5.2 Advanced approach

Conventional agro-waste management reduces waste volume and produces value-added goods. However, operational issues, environmental implications, and expenses must be considered. Therefore, an advanced approach is needed to improve the ecosystem. Nutraceuticals, health-beneficial food-derived compounds, are gaining importance due to increasing diet-related health issues. Extracting these compounds, including antioxidants, dietary fibers, fatty acids, and polyphenols, from fruit and vegetable waste is challenging but explored through various traditional and non-thermal methods (Sridhar *et al.*, 2021). The global interest in dietary fibers from fruits and vegetables is increasing due to their positive effects on intestinal health and sugar absorption. However, the variable chemical composition of feed complicates the analysis of fiber concentrations. Polyphenols, diverse bioactive molecules used in nutraceuticals, offer protection against chronic degenerative and cardiovascular diseases (Swallah *et al.*, 2020). The phenolic content of fruit/vegetable waste can be beneficial for preservatives, additives, and supplements (Sir Elkhatim, Elagib, and Hassan, 2018). Extracting bioactive compounds can boost the economies of developing countries. While micro and nanoencapsulation techniques are promising, their cost-effectiveness and practicality are crucial for successful scale-up.

In addition, metallic nanoparticles, with their unique properties, are utilized in various fields including medicine and drug delivery. Their small size and large surface area enhance reactivity and porosity, facilitating successful cellular barrier penetration. They are synthesized through methods such as microwave irradiation and solvothermal degradation (Usman, Aziz, and Noqta, 2019). The shift toward green nanoparticle production using vegetable or fruit waste, due to its sustainability and cost-effectiveness, is gaining significant attention (Karimi, Sadeghi, and Kokini, 2017). Antibacterial gold nanoparticles from *Pergularia daemia* leaf extract were bacteria-resistant (Rajendran, 2017). Controlled green synthesis employing mint leaves on cotton fabric produced gold nanoparticles with UV protection, antibacterial sensitivity, and cytotoxicity (Boomi *et al.*, 2019). Recent studies have reported the successful synthesis of carbon nanoparticles from rice husk waste, exhibiting bright fluorescence and high photostability, making them ideal for bioimaging and drug delivery applications (Zhang *et al.*, 2020). Additionally, titanium dioxide derived from tangerine peel waste has shown low toxicity and high photochemical stability (Rueda *et al.*, 2020). Furthermore, zinc oxide has been efficiently extracted from waste of oranges, grapefruits, and tomatoes, with tomato waste showing the fastest synthesis rate (Nava *et al.*, 2017). Nanoparticle synthesis using microorganisms is less favored due to high maintenance, and more research is needed on their toxicity and the economic feasibility of scaling up production from agro-waste extracts.

19.6 Agricultural waste generated value-added products in relation to SDGs

19.6.1 SDGs and agricultural waste to wealth

Food is a must for all life to survive. Global food production has increased owing to population augmentation leading to increasing the generation of food and agricultural waste. The development of value-added products from waste materials



FIGURE 19.2 **Transforming agro-waste into wealth in relation to SDGs.** Long arrow indicates the direct relevance of the agro-waste generated value-added products to attainment of the respective SDGs and short arrows indicates the rest of the non-relevant SDGs.

has emerged as a key component in meeting the Sustainable Development Goals (SDGs) approved by the United Nations with the expectation that everyone will live in peace and prosperity. In this regard, the concept of waste management entwined with a circular economy and sustainability has proven to be a holistic approach in reducing the overburden of waste generated from various agro-industries. Food waste and successive waste management are great concerns and directly related to several agendas of the total 17 SDGs (Figure 19.2).

According to Dantas *et al.* (2021), the 17 SDGs may be classified into one of three main areas, namely the economy, society, or biosphere. If we want to achieve economic growth of the country while simultaneously using the concept of sustainable development, we should definitely reduce the ecological footprint by changing the way we produce and consume goods and resources. For instance, agriculture is the largest consumer of water in the world, and irrigation currently requires almost 70% of all freshwater involved in human consumption. However, while some of us are throwing food away, much of the world's population still consumes too little to cover even their basic needs. There is a need to significantly reduce global food waste, especially from retailers and consumers. This will be administered by newly created more efficient production and supply chains, which can help with food security. At the same time, they will move us toward a more efficient economy in terms of resources and integration with all the relevant agenda of SDGs ("Responsible Consumption, Production," 2022).

19.6.1.1 Contribution in income generation options

Waste is a particular area of concern, and the foremost problem is dealing with waste. By reusing it through recycling, we can process at least part of the waste materials and use them to our advantage. In this regard, a new direction of the circular economy is coming to the fore.

The circular economy (CE), as a kind of new economic form, is based on the principles of diversity, resilience, and comprehensive thinking. The CE requires an intersection of the biological, technological, and material spheres. It supports a cyclical relationship and the transformation, distribution, utilization, and regeneration of available materials. It must be noted that there is no perfect and closed system that allows every resource to be reused; with notions such as the CE, there are both advantages and limits to their application (Corral *et al.*, 2022).

Food waste is one of the biggest global challenges. SDG 12 is related to food waste and commits the global community to halve food waste generation at the consumer and retail levels, while aiming to reduce food losses along the supply chain (Papamonioudis and Zabaniotou, 2022). For the area of circular economy, SDG 12 is the most suitable in terms of content. The European Union published an action plan that clearly states that the CE is a system-wide solution strongly directed to promoting sustainable consumption and production modalities and, therefore, contributing to the achievement of the targets set for this particular SDG (Dantas *et al.*, 2021). The CE is a kind of new economic form and economic development model (Corral *et al.*, 2022) aimed at the efficient use of resources (Banaitė, 2016) through waste minimization, long-term value retention, reduction of primary resources, and closed loops of products, product parts, and materials within the boundaries of environmental protection and socioeconomic benefits (Morseletto, 2020). Suchek *et al.* (2021) argue that the CE provides a reliable structure for radically improving the current business model within the scope of developing a preventive and regenerative eco-industry, as well as boosting well-being based on recovered environmental integrity. The circular economy is an important support tool for economic growth, and it is in line with sustainable environmental and economic development (Korhonen, Honkasalo, and Seppälä, 2018). The transition to CE is not easy for any economy. It represents a systemic change that seeks not only to reduce the impacts of the linear economy but also to strengthen long-term resilience and create economic and business opportunities while returning environmental and social benefits (Suchek *et al.*, 2021).

Around 30% of the food we produce globally every day is wasted, and yet there is still much of the world that is undernourished. Mitigation efforts can be about more than just streamlining production to save money; upcycling food waste into new ingredients presents an opportunity to create additional revenue streams. Food loss and waste can occur at any point between where it is produced and where it is consumed. To help prevent that, existing processes, new technologies, and innovative steps can be applied into practical, technological, and educational initiatives that can help reduce food loss and waste, resulting in income generation options.

19.6.1.2 Food safety

Nowadays, we are facing many challenges in food production for an increased population. Besides economic aspects, food security, and climate change impact on crop production, food safety is another major challenge. Economic growth inevitably influences the food chain. Growing demand along with changes in lifestyle and health consciousness encourage use of packaged and pre-prepared foods. The needs of environmental protection from waste generated are largely overlooked, and a lack of knowledge about the impact on the environment and its health effects constitute food safety problems. Food production and waste generation directly affect resource (i.e., energy and water) consumption and often contaminate the environment. More pressure on food production has inculcated the use of pesticides, herbicides, antibiotics, and chemical fertilizers that add to current global pollution. At least half of food grown is discarded before and after it reaches consumers. It is estimated that one-third to half of landfill waste comes from the food sector (Lin, Huang, and Wahlqvist, 2009). This landfill waste releases greenhouse gases (GHG) as well as leachate, which worsens soil and water quality and safety. Pharmaceutical and chemical contamination from residential, industrial, and agricultural sources make their way into nearby water and soil and can eventually affect our food systems. Existing waste management strategies warrant more stringent norms for waste reduction at the source. Awareness through education could reduce food waste and its consequences.

19.6.1.3 Sustainable environment

Waste materials are either usable or unusable products left behind after production or formulation of the main products produced by human activities. A part of waste materials that is totally unsuitable for use is known as spoiled product. Economic development and rising living standards, especially in the developing states, have led to an increase in the quantity and complexity of generated waste. Generally, waste is of two types: both hazardous and nonhazardous. The wastes are of major concern to keep the environment protected; thus, this part is generally not targeted for reuse. The nonhazardous waste has the potential to be used in many forms with little or no threat to the environment and human health. Industrial diversification produces substantial quantities of industrial waste, including biomedical waste, which have severe environmental and human health consequences. There are several sources of waste generation including the home we reside in, as well as public places, agricultural fields, hospitals, industry, etc. The waste can be divided into three major categories: (1) organic (all kinds of biodegradable waste), (2) dry (or recyclable waste), and (3) biomedical (or sanitary and hazardous waste). These may pollute groundwater quality and cause air pollution by emission of greenhouse gases.

The impact of agricultural waste on the environment depends not only on the amounts generated but also on the disposal methods used. Some of the disposal practices pollute the environment. For example, agricultural waste burning is a common practice in the undeveloped countries, but it is a source of atmospheric pollution. Agricultural waste burning releases pollutants such as carbon monoxide, nitrous oxide, nitrogen dioxide and particles (smoke carbon). These pollutants are accompanied by the formation of ozone and nitric acid, hence contributing to acid deposition and thereby posing risk to human and ecological health. It can be resolved by utilizing it as an animal feed by applying pyrolysis treatment, making cardboard, paper, and other products. It can be used as a mulching material for various crop cultivation and also can be used as organic manure by tillage in the field.

19.6.1.4 Biodiversity

The food system already threatens more wild species than any other human activity through habitat clearance and fragmentation for farmland, overexploitation of marine and terrestrial species, and widespread pollution. Rapidly accelerating population sizes and incomes in many tropical countries will lead to great increases in food demand. Unless the current trajectories of crop yields in these countries are rapidly accelerated, the land clearing needed to meet this food demand will destroy and fragment large areas of remaining natural ecosystems and place many species, including many of the world's remaining large mammals, on trajectories toward extinction. Numerous agricultural studies in these countries have shown that existing yield gaps can be closed in environmentally efficient manners and that a major barrier is access to the agronomic practices and inputs required for higher yields. An integrated program of international agricultural aid, national zoning and land planning, and programs to improve health and reduce food waste would help assure both the conservation of the cradles of Earth's biodiversity and the health and security of those who currently are some of the poorer and less secure of Earth's people.

Today's key challenge is how to increase production to meet the growing demand for food, feed, and bioenergy while conserving biodiversity and reducing the pressure on natural resources and ecosystems. Biodiversity is the sum of all terrestrial, marine, and other aquatic ecosystems, species, and genetic diversity. It includes the variability within and among living organisms and the ecological complexes of which they are part. Each ecosystem is characterized by complex relationships between living components such as plants and animals and nonliving components such as soil, air, and water. "Agriculture" comprises all aspects of crop and livestock farming, fisheries, aquaculture, and forestry. Agricultural biodiversity includes all the components of biological diversity of relevance to food and agriculture together with the components of biological diversity that constitute the agroecosystem: the variety and variability of animals, plants, and microorganisms, at the genetic, species, and ecosystem levels, that sustain the functions, structure, and processes of the agroecosystem. This diversity has been shaped by farmers and communities for millennia and remains a key element of the livelihood strategies of poor, small-scale farmers throughout the world. Agricultural biodiversity, including wild relatives of genetic resources, is a fundamental resource for the continued improvement of varieties and breeds, and it is needed to cope with changes for feeding a huge population.

This agricultural ecosystem is now in threat because every year, enormous biomass as agro-byproducts are accumulated in large quantities and cause environmental pollution. This also causes loss of potentially important materials that can be used for the production of a number of valuable products, such as food, feed, fuel, and a variety of chemicals and bioactive compounds. The protection of the environment as well as biodiversity toward the aim of sustainability is one of the most discussed topics in the area of waste management. The sustainable solutions for waste management range from waste prevention, waste minimization, cleaner production, and zero emissions systems. The sustainable solutions for waste management include environmentally sound management of waste, applying zero emission industrial ecosystems, agro-based industrial systems and, most importantly, reuse, recycling, composting, bio-digestion, bio-extraction, and bio-refineries, among others, for ensuring the safe and reliable resources for biodiversity.

19.7 Future potential of bioconversion of agricultural waste using biotechnologies

19.7.1 Biotechnology tools used for agricultural waste conversion strategies

19.7.1.1 Bioconversion

The biological pretreatment technique is both environmentally friendly and energy-efficient, in contrast to current chemical and thermal pretreatment methods. This section of the chapter examines the bioconversion technologies used to convert bio-waste into biofuels and chemicals. Bioconversion technologies, including pyrolysis, gasification, and fermentation, have emerged to transform waste materials into valuable commodities like biofuels, fertilizers, and chemicals. These technologies present an alternative to conventional energy production methods and decrease reliance on nonrenewable

resources (Kataya *et al.*, 2023). An evaluation is conducted on the emerging breakthroughs in bioconversion processes of four key conversion pathways: microbial, enzymatic, fermentation, and composting conversion strategies.

19.7.1.1.1 Microbial bioconversion. Microbial bioconversion techniques are increasingly being used to address the limitations and environmental issues associated with traditional chemical processes. This technique employs a variety of microorganisms, such as bacteria, yeasts, fungi, and microalgae, known as microbial enzymes, for the conversion of bio-waste into valuable biofuels and chemicals (Palve, Arukula, and Gupta, 2021). The conversion of lignocellulosic bio-waste into biofuel is a sustainable alternative to fossil fuels due to the high availability of bio-wastes and its lesser environmental impact (Mahish *et al.*, 2024). The bioconversion process of lignocellulosic bio-wastes to bioethanol is more complex than the conversion of starch-based bio-wastes as it involves four steps: pretreatment, hydrolysis of cellulose and hemicelluloses to soluble monomers (pentoses and hexoses), bioconversion of these monomers to bioethanol through fermentation, and purification of the final products. Bioethanol, a type of biofuel, is a significant material that can substitute petroleum and is considered a clean liquid fuel.

19.7.1.1.2 Enzymatic bioconversion. Enzymatic bioconversion, a process that occurs after pretreatment, effectively transforms polycarbohydrates into soluble sugars, specifically pentoses and hexoses. Specific microbes, known for their bioconversion abilities, are used in this process. These microbes produce special enzymes that act as biocatalysts, facilitating eco-friendly and economical reactions. These microbial enzymes are classified based on their temperature, alkalinity, and acidity preferences as thermophilic, alkalophilic, and acidophilic.

19.7.1.1.3 Fermentation bioconversion process. The fermentative production of biofuels and biopolymers from bio-waste and byproducts is commercially attractive. Bio-waste and byproducts from industries like pulp, paper, and food can be used for biodiesel and bioethanol production. Bioethanol, a biofuel and platform chemical, is an alternative to conventional energy sources. It is produced through the fermentation of various carbon resources like lignocellulosic materials, starch crops, and sucrose-based feedstocks. The cellulosic part of lignocellulosic material is transformed into polysaccharides, which are then converted to bioethanol through hydrolytic and fermentation processes. Lignocellulose is typically hydrolyzed using an acid treatment, and the resulting sugars are used in a bioethanol fermentation process with microbes like yeast.

19.7.1.1.3.1 Microbial pigments production. The techniques of submerged fermentation (SMF) and solid-state fermentation (SSF) are employed for the production of microbial pigments. Microorganisms, preferred over plants, are excellent sources of natural pigments such as carotenoids, prodigiosin, flavins, violacein, and anthraquinones (Tuli *et al.*, 2015). These pigments, alternatives to synthetic colors, are used in the food and beverage industry and textile industry and have medicinal properties (Narsing Rao, Xiao, and Li, 2017). They are also explored as biological substitutes in cosmetics (Gupta *et al.*, 2019). Agro-industrial residues are used for deriving these pigments, with research focusing on increasing production (Lopes and Ligabue-Braun, 2021). The wide applicability of microbial pigments has led to a surge in production, but there is a need for novel strains, stability testing, and improved commercial production.

19.7.1.1.3.2 Industrial enzyme production. Enzymes act as potential biocatalysts across diverse industries, and sustainable and economically efficient strategies for the production are emphasized (Wen, Liao, and Chen, 2005). The use of agro-industrial residues in microbial fermentation significantly reduces raw material costs and enables the production of enzymes like cellulases, pectinases, laccases, xylanases, proteases, α-galactosidases, and lipases (Mehmood *et al.*, 2019). For instance, pectinase was produced using sweet lime fruit peels and orange pomace, while cellulase was produced using orange waste, sugarcane bagasse, and tobacco waste (Salomão *et al.*, 2019).

19.7.1.1.3.3 Biocontrol agent production. Worldwide, microbial fermentation techniques are being used to develop innovative biocontrol agents including bio-pesticides and bio-insecticides from agricultural leftovers like sugarcane bagasse and coffee husks. *Beauveria bassiana* fungi are used to create bio-pesticides from agricultural residue for banana, coffee, soybean, and sugarcane crops (Santa *et al.*, 2005). Similar research examined the generation of bio-insecticides from *B. bassiana* and *Trichoderma harzianum* in packed bed reactors using rice husk as a substrate (Sala *et al.*, 2020). Both *B. bassiana* and *Isaria javanica* fungal strains were employed to create bio-insecticides from palm kernel cake utilizing solid-state fermentation. Ndao *et al.* (2017) conducted a pilot-scale investigation that successfully produced Bt-based bio-insecticides from *Bacillus thuringiensis* subsp. *kurstaki* using starchy industrial effluent as a growth substrate.

19.7.1.1.3.4 Bioactive compounds production. Bioactive compounds like phytochemicals and phenolic compounds, found in fruits and vegetables, have antioxidant potential and health benefits, making them attractive for the food and pharmaceutical industry. Agro-industrial residues, such as citrus peels and jackfruit seeds, are rich sources of these compounds. Selected microorganisms are employed for retrieving bioactive compounds from agro-industrial residue. Solid-state fermentation (SSF) using various fungi enhances the free radical scavenging properties of these wastes. The concentration of antioxidants like gallic acid and ferulic acid increases significantly after SSF of rice bran (Schmidt *et al.*, 2014). Recent research focuses on producing and enhancing bioactive compounds from economical substrates.

19.7.1.2 Synthesis of nanoparticles

Nanotechnology, a burgeoning field, deals with nanoparticles of 1 to 100 nm size, exhibiting high surface reactivity due to their high surface-to-volume ratio, and finds applications in various industries (Chaturvedi, Dave, and Shah, 2012). The green technology approach utilizes microorganisms and plant extracts, including agro-industrial wastes like peels and rice husk, for nanoparticle synthesis (Khandel *et al.*, 2018). Biopolymers like chitosan, cellulose, xylan, etc., are also gaining popularity in nanoparticle production (Harish, Uppuluri, and Anbazhagan, 2015). Examples include the production of silver, gold, platinum, and palladium nanoparticles using various plant extracts (Yang, WeiHong, and Hao, 2014). These nanoparticles, ranging from 40 to 100 nm, exhibit antimicrobial properties and potential for bioremediation (Tolba *et al.*, 2015). However, challenges remain in result reproducibility and size variations.

19.7.1.3 Biosurfactants

Biosurfactants, surface-active molecules, enhance the bioavailability and solubility of polar organic compounds. They are biodegradable, less toxic, and highly selective, making them advantageous over synthetic surfactants. They find applications in various industries, including food, medical, cosmetics, and petroleum. However, their high production cost limits their use. The use of low-cost agro-industrial substrates for biosurfactant production through microbial processes can make the process sustainable and cost-effective. Studies have reported the production of biosurfactants from *B. subtilis* ANR 88 using molasses, *Serratia nematodiphila* using pretreated rice straw hydrolysate, and *Paneibacillus* sp. D9 using waste coconut and sunflower oil (Panjiar *et al.*, 2020; Jimoh and Lin, 2020). Other parameters, like microbial strains, process design optimization, and extraction methods, also need to be considered for efficient and productive biosurfactant production.

19.7.1.4 Strain improvement through genetic and metabolic engineering

Genetic and metabolic engineering are pivotal in augmenting the production of valuable products from waste (Álvarez-Cao *et al.*, 2018). Techniques such as CRISPR/Cas9 editing have been employed to genetically modify microbial cells, thereby enhancing the production of industrially significant metabolites (Fokum *et al.*, 2019). Metabolic engineering, which integrates system biology, synthetic biology, and evolutionary engineering, is another promising approach. It facilitates the development of high-performance microbial cell factories for bioproduct synthesis. Various forms of biomass and gases can be efficiently used as raw materials for this purpose (Ko *et al.*, 2020). The rate-limiting step of a metabolic pathway can be optimized to enhance metabolite production. This can be achieved by manipulating gene expression, regulation, or knocking out the genes for competing pathways (Huccetogullari, Luo, and Lee, 2019). Such strategies have led to the high production of nutraceuticals, polyphenols, and carotenoids from several metabolically engineered strains (Yuan and Alper, 2019). The application of system biology or omics approaches can further increase the product yield (Yang *et al.*, 2020).

19.7.1.5 Co-culture of microbial strains

Co-culturing distinct microbial strains is an innovative bioprocessing technology that improves product quality and production by utilizing microorganisms' unique traits. Such microbial consortia reduce strain metabolic load and improve substrate utilization. *Trichoderma reesei* and *Escherichia coli* co-cultivation produces isobutanol directly from cellulosic biomass (Sharma *et al.*, 2019). A fermentation-based consortia of *Candida utilis* and *Geotrichum candidum* biosynthesized protein from yellow wine waste (Zhu *et al.*, 2020). Co-cultures of gut microbes, adapted to food waste, can be repurposed for chemical production, offering an alternative to isolated industrial fermentations. These co-cultures potentially yield higher outputs due to metabolic interactions. Computational assessments show benefits for all organisms in co-cultures, including increased biomass fluxes and emergent or increased production of commodity chemicals such as butanol, methane, formaldehyde, propionate, hydrogen gas, and urea. These overproducing co-cultures are rich in mutualistic and commensal interactions (Perisin and Sund, 2018).

19.7.2 Cost-effective analysis of bioconversion and conventional approaches

The management of agricultural waste poses considerable concerns, not only in agriculture but also in other domains, such as ecosystem preservation and sustainability. This waste can be categorized according to different sources, such as field waste, consisting of various parts of crops such as leaves, stems, stalks, husks, and roots; industrial waste, generated during the processing of crop or animal products, including byproducts from the food industry; livestock waste, consisting of materials like bedding/litter, animal carcasses, and wastewater from animal sanitation; as well as food waste, consisting of edible portions of food that are discarded at various stages of the food supply chain, among others (Duque-Acevedo *et al.*, 2020). The disposal of agricultural residues, byproducts, and organic waste presents significant environmental, health, and economic issues. Different studies have shown that underutilized and/or untreated agricultural waste is often disposed of by burning, dumping, or landfilling it following conventional approaches (Awogbemi and Von Kallon, 2022a). But these practices significantly contribute to greenhouse gas emissions (GHGs), the production of undesirable gaseous byproducts, soil and waterway pollution, endangering wildlife that ingests it or becomes entangled in it, and the outbreak of diseases, and these consequences pose a threat to both the environment and animal and human health through various pathways (Koul, Yakoob, and Shah, 2022). However, recent developments using a bioconversion approach have highlighted the immense potential for its valorization as a sustainable solution. The bioconversion concept of agricultural waste valorization involves the process of its reuse and recycling into valuable products or energy rather than its disposal as a useless byproduct. The goal is to reduce waste generation, minimize environmental impact, and create economic opportunities by turning agricultural waste into valuable resources, while the conventional approach only works on one way to reduce the waste rather focusing on the environmental issues. Therefore, by valorizing agricultural waste following the bioconversion process, farmers and agricultural industries can contribute to sustainable practices, resource efficiency, and the circular economy more economically than conventional approach (Haque, Fan, and Lee, 2023).

However, despite the significance of bioconversion over the conventional approach, there remains a critical need for thorough assessments to evaluate the efficacy and sustainability of each technology, taking into account its environmental impact, energy efficiency, economic viability, and scalability. Various assessment methods, such as life cycle assessment (LCAs), life cycle analysis (LCAn), net energy ratio (NER) calculations, and life cycle costing (LCC), as well as techno-economic assessment (TEA), should be considered, as they may serve as essential tools in this evaluation process, providing insights into the emissions, energy balance, and cost-effectiveness of the conversion approaches in more precise and comprehensive ways.

19.8 Challenges and future research directions

Agricultural waste valorization into bioenergy resources presents promising eco-friendly and economically feasible benefits. However, the current progress in agricultural waste valorization technologies still holds significant gaps in need of improvement. One of these challenges lies in the pretreatment of agricultural waste biomass to optimize its conversion rates and lower the required energy consumption throughout the process while enhancing both the quantity and quality of the output (Awogbemi and Kallon, 2022a). Given the critical role of agricultural waste in biofuel production, innovative and enhanced pretreatment techniques are essential to facilitate more efficient degradation and conversion of crop residues and other agricultural waste into valuable products. In line with Agriculture and Technology 4.0, the integration of cutting-edge technologies, such as machine learning and artificial intelligence, the Internet of Things (IoT), and robotics, is essential to enhance various aspects of the agricultural waste conversion process, optimizing the cost efficiency, time management, and labor requirements and consequently boosting the conversion efficiency and product quality. This will require collaboration and interdisciplinary research (Ufitikirezi *et al.*, 2024). Another important recommendation is that it is imperative for governments at all levels to promote awareness among farm owners regarding the advantages of converting agricultural waste into valuable products. As a result, this will secure a steady and sustainable stream of agricultural waste, thus providing a reliable source of low-cost feedstock for biofuel production. To fully realize the potential of agricultural waste valorization, continued research and development are needed to optimize the technologies, improve their efficiency, and explore new applications. Further studies are recommended for thorough assessments to evaluate the efficacy and sustainability of agricultural waste valorization technologies. Assessment methods such as life cycle assessment (LCAs), life cycle analysis (LCAn), net energy ratio (NER) calculations, and life cycle costing (LCC), as well as techno-economic assessment (TEA), are recommended (Watson *et al.*, 2020) Collaboration between academia, industry, and policymakers is crucial to create supportive frameworks and incentives for waste valorization initiatives.

19.9 Conclusions

The growth of the global population alongside expanded agricultural and food processing activities has driven a notable surge in agricultural waste production, leading to increased environmental concerns and greenhouse gas emissions. This review provided a comprehensive overview of sustainable and eco-friendly approaches to the efficient valorization of agricultural waste through bioenergy conversion. It illustrates the feasibility of converting agricultural residues into various bioenergy resources suitable for diverse uses to supply the currently increasing energy demand. The valorization of agricultural waste holds significant potential for addressing the challenges of increasing energy production demand, waste management, and environmental sustainability, as energy production's interaction with the environment is one of the most important steps needed to achieve sustainable development. With this ability and many other economic and social advantages, bioenergy can be considered a suitable option. The adoption of green innovations and technologies can help mitigate the harmful effects of waste on the environment and human health. Various methods, such as pyrolysis, torrefaction, gasification, anaerobic digestion, and fermentation, offer economically viable ways to transform agricultural waste into valuable resources. Pyrolysis and torrefaction processes can convert agricultural waste into bio-oil, biochar, and other byproducts, offering alternative energy sources and soil amendments. Gasification enables the production of synthesis gas or gaseous fuels from waste biomass, contributing to clean energy generation. Anaerobic digestion converts organic waste into biogas and digestate, providing renewable energy and organic fertilizer, while fermentation can transform waste biomolecules into ethanol and other biofuels. By embracing these opportunities, we will not only address energy demand but also contribute to a more sustainable and circular agricultural system that minimizes waste and environmental impact.

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Chapter 20

Agricultural waste as a renewable resource: Biomass and biofuel production

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Chapter Outline

20.1. Introduction 333
20.2. Agricultural waste and environmental pollution 334
20.3. Valorization of agricultural waste by microalgae cultivation 335
20.4. Solid-state fermentation of crop waste by high-value microorganisms 339
20.5. Production of hydrogen gas by using agricultural waste 341
20.6. Assessment of the greenhouse gas emission 342
20.7. Conclusion and future prospects 344
References 345

20.1 Introduction

With the continuous growth of the global population and the rapid development of agricultural production, the generation of agricultural waste is rapidly increasing year by year (Koul, Yakoob, and Shah, 2022). Agricultural waste refers to the general term for waste generated in agricultural production, agricultural product processing, livestock and poultry breeding, the lives of rural residents, and so on (Azadbakht, Safieddin Ardebili, and Rahmani, 2023; Maji *et al.*, 2020). To our knowledge, agricultural wastes mainly include crop residue, livestock manure, processing waste generated during agricultural processing, and rural domestic waste. Agricultural waste, which is generated not only in the industrialized countries but also in the non-industrialized countries, poses a more serious threat to the global environment by causing water pollution and soil contamination (Koul, Yakoob, and Shah, 2022). For example, if the agricultural waste is placed near the waters, decomposition of agricultural waste can release a large number of organics, which may cause the eutrophication of natural waters. In addition, pollutants released by the decomposition of agricultural waste could cause the soil non-point source pollution (Mengqi *et al.*, 2023). Therefore, to promote the sustainable development of agriculture and human society, agricultural waste should be treated properly.

In fact, a variety of technologies or methods, such as burning crop straw and landfilling agricultural waste, have been developed to attenuate the environmental pollution caused by agricultural waste (Capanoglu, Nemli, and Tomas-Barberan, 2022; ChooChuay *et al.*, 2022). However, the aforementioned technologies or methods may cause secondary pollution or underutilize the resources contained in agricultural waste. For example, crop straw burning could convert crop straw to ash, which can be further used as fertilizer in agricultural activity, but it also causes serious air pollution. Therefore, in some countries, crop straw burning is forbidden to prevent air pollution (Xinxin *et al.*, 2020). In addition, via landfilling agricultural waste, the decomposition of organics can be accelerated, but this process can exacerbate the pollution of soil and underground water (Siddiqua, Hahladakis, and Al-Attiya, 2022). Therefore, to promote the sustainable development of

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agriculture, technological innovation that is necessary to achieve the valorization of agricultural waste has become a hot issue in current research.

This chapter aims to explore the innovative technology of increasing the value of agricultural waste and its effects in practical applications. First, this chapter will provide an overview of the types and characteristics of agricultural waste and the necessity of resource utilization. Then, this chapter will introduce in detail the resource utilization technology of agricultural waste, including biomass energy conversion technology, organic fertilizer production technology, and biological feed production technology (Figure 20.1). Next, carbon emissions of these innovative technologies are discussed to evaluate their sustainability and applicability. Finally, this chapter will assess the effects of these technologies in practical applications, discuss their existing problems and challenges, and provide prospects and suggestions for the valorization of agricultural waste, with a view to providing a reference for future research and practice.

20.2 Agricultural waste and environmental pollution

20.2.1 Classification of agricultural waste

Agricultural waste can be mainly classified into three categories, including animal manure, crop waste, and agricultural product processing waste. In general, many agricultural wastes are enriched with organic pollutants, which can cause water eutrophication and ecological disasters.

Livestock and poultry manure is an important byproduct produced in the livestock and poultry breeding process. It covers feces, urine, and related sewage. These manures are not only the main source of environmental pollution in the livestock and poultry breeding industry but also a potential resource with high value (Vaishnav *et al.*, 2023). In general, animal manure consists of two categories: First, during the feeding process of livestock and poultry, a portion of digested

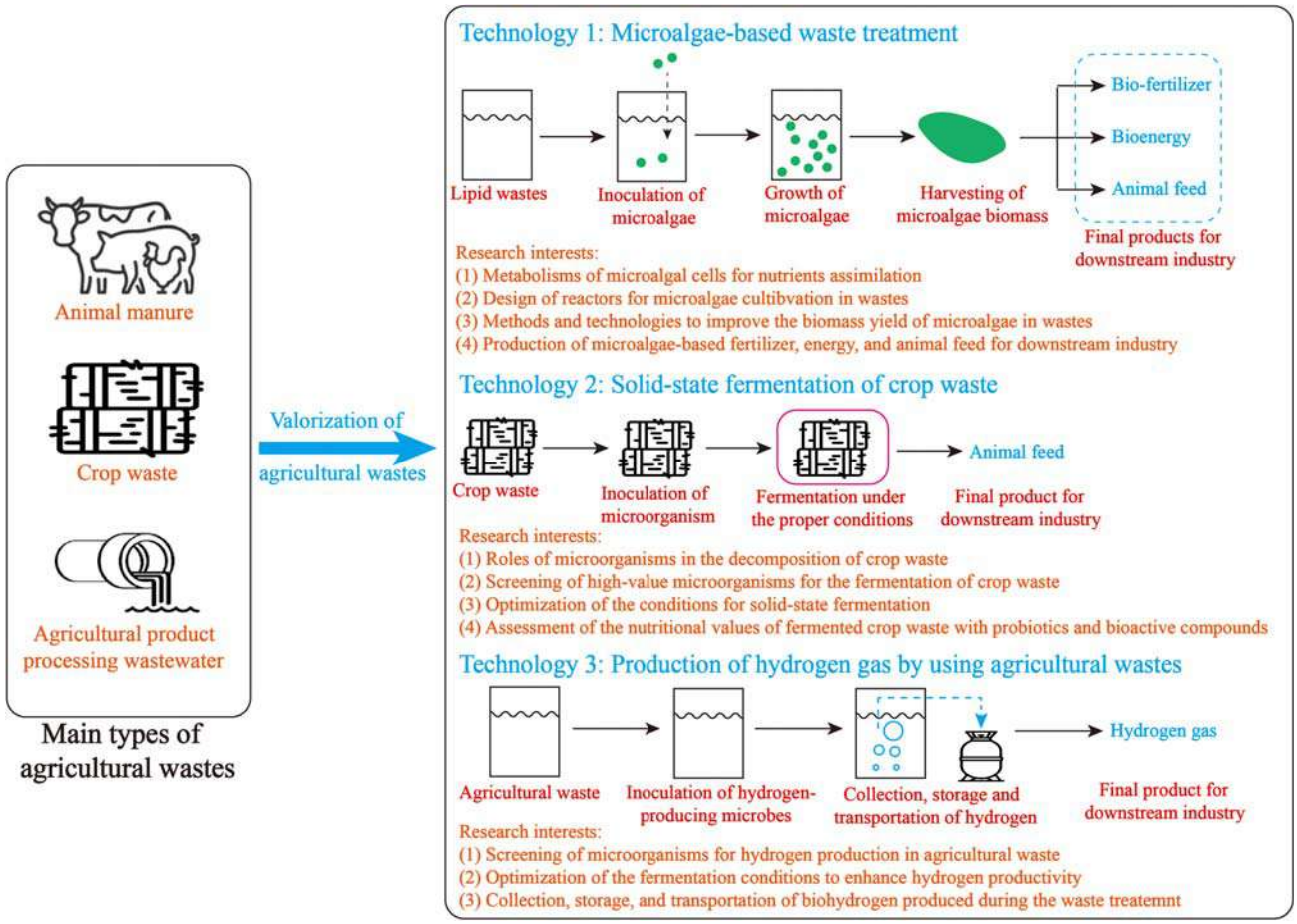


FIGURE 20.1 Resource utilization technology of agricultural waste, including biomass energy conversion technology, organic fertilizer production technology, and biological feed production technology. Resource utilization technology of agricultural waste

feed, which cannot be absorbed by animals, will be converted to feces and urine. Second, to maintain a comfortable environment for animal breeding, water is used to clean the pig house, sheep house, and so on. As a result, a large volume of wastewater enriched with organics is produced. It should be noted that in animal breeding wastewater, there are a variety of pathogenic microorganisms and parasite eggs, which may cause serious water pollution if the wastewater is discharged without appropriate treatment (Esperón *et al.*, 2020).

Crop waste, which is an important byproduct in the agricultural production process, should be treated appropriately after crop harvesting. In recent years, with the fast growth of populations worldwide, crop production is increasing rapidly. As a consequence, the production of crop waste is becoming a serious environmental problem. Although crop waste could not directly cause soil pollution or water pollution, it cannot be easily degraded (Shinde *et al.*, 2022). The discard of crop waste on farmland will lower the land utilization efficiency.

Agricultural product processing waste is generated by the agricultural product processing industry. According to the previous studies, there are numerous agricultural product process wastes, such as slaughterhouse wastewater, dairy processing wastewater, starch production wastewater, molasses, and so on, with very different physical and chemical properties (Lu and Xiao, 2022; Lu *et al.*, 2023, 2015, 2016). For example, slaughterhouse wastewater is enriched with nitrogen and a high ratio of nitrogen to carbon, while molasses has a high content of organic carbon (Liu and Cheng, 2022; Selormey *et al.*, 2021). In the view of the present authors, due to the high content of organics in agricultural product processing waste, it poses a serious threat to the environment.

20.2.2 Environmental pollution caused by agricultural waste

Due to the different properties of agricultural wastes, the effects of agricultural waste on the environment are complicated. In general, the environmental pollution caused by agricultural waste can be classified into three categories, water pollution caused by the discharge of wastewater, soil pollution caused by organics decomposition during compositing process, and air pollution caused by crop waste burning.

First, the discharge of agricultural product processing wastewater or animal manure enriched with nitrogen, phosphorus, and organic carbon can cause the eutrophication of natural waters. Consequently, water pollution may disturb the ecological balance in the environment and cause ecological disasters. It was reported that the algal bloom in many regions could be attributed to the eutrophication in natural waters. Furthermore, pathogenic microorganisms in agricultural product processing wastewater and animal manure can dramatically change the structure of microbial community in natural waters.

Second, during the composting process, with the decomposition of organics contained in wastewater or animal manure, soil can be contaminated. The decomposition of organics can release a large amount of nutrients, such as nitrogen, phosphorus, and organic carbon, which enter the soil or underground water. If these nutrients, particularly nitrogen and phosphorus, released from wastewater and manure are washed into water bodies with rainwater, they will cause eutrophication of water bodies, trigger massive algae reproduction, and destroy the balance of water ecology (Y. Wang *et al.*, 2021). Furthermore, with the release of nutrients from agricultural waste during the composting process, due to the existence of anaerobic bacteria, greenhouse gases CH_4 and CO_2 can be released.

Third, crop waste burning will produce a large amount of harmful substances, such as nitrogen oxides, sulfur dioxide, hydrocarbons, and smoke, which accumulate in the atmosphere, causing air pollution and having adverse effects on human health (Abdurrahman, Chaki, and Saini, 2020). For example, the polluted air caused by crop waste burning can cause coughing, chest tightness, tears, and other symptoms. Under the action of sunlight, these pollutants in the air may also produce secondary pollutants, such as ozone, further exacerbating air pollution (H. Wang *et al.*, 2021).

Fortunately, the development of innovative technology has been regarded as an applicable strategy to solve environmental pollution and achieve the valorization of agricultural wastes. For example, as two of the countries with the largest agricultural waste output in the world, India and China produce a huge amount of agricultural waste every year. The governments of India and China have realized that if these agricultural wastes are effectively used, they can not only reduce environmental pollution but also provide new resources and power for agricultural production and rural economic development (Afolalu *et al.*, 2021; Kapoor *et al.*, 2020). Therefore, in recent years, research funds have been provided by the governments and institutes in China to promote the technological innovations in agriculture. In industry, agricultural waste is being regarded as a valuable resource instead of pollutant. Such a model not only creates ecological benefit but also creates economic benefit.

20.3 Valorization of agricultural waste by microalgae cultivation

Microalgae can be employed to recover nutrients from some of the wastes generated in agricultural activities. According to previous studies, microalgae have been successfully grown in a variety of agricultural wastes, such as animal manure,

molasses, and crop straw hydrolyzate (Lu and Xiao, 2022; Lu *et al.*, 2015, 2016; Yew *et al.*, 2020). In this section, the mechanisms of microalgae-based agricultural waste treatment and the bioreactors for microalgae cultivation are introduced. In addition, some examples of growing microalgae for agricultural waste treatment and biofuel production are discussed.

20.3.1 Microalgae for nutrient recovery in waste

Microalgae are a group of unicellular microorganisms with the ability of performing autotrophic, mixotrophic, and heterotrophic growth (Abreu *et al.*, 2022). In nature, microalgae are diverse and widely distributed from the poles to the equator in rivers, lakes, the ocean, soil, and even deserts. Up to now, a number of microalgal species have been discovered in the waste stream, including agricultural wastewater, industrial wastewater, mining wastewater, and so on. Microalgae that survive in wastewater not only have strong vitality but also have many unique biological properties and ecological functions. First, microalgae growth consumes a large amount of nutrients, such as nitrogen, phosphorus, organic carbon, and some metal ions, in wastewater. Compared with hydroponic plants, microalgae own a much higher rate of nutrient assimilation, resulting in higher efficiency of wastewater remediation (Udayan *et al.*, 2023). Second, microalgae can use light energy to perform photosynthesis, converting carbon dioxide and water into high-value biomass and oxygen. Accordingly, the carbon footprint of wastewater treatment can be reduced. Third, some microalgal species are tolerant to the harsh environment of wastewater, indicating the practical feasibility of growing microalgae in wastewater for water quality improvement (Malavasi, Soru, and Cao, 2020). Therefore, microalgae that play an important role in the ecosystem can be employed to absorb and transform nutrients and some harmful substances in wastewater for environmental protection.

It should be noted that not all the nutrients contained in agricultural wastes can be assimilated by microalgal cells. For example, a portion of a nutrient that is in the form of suspended solids in agricultural waste could not be directly absorbed by algal cells. In practice, to improve the nutrient recovery efficiency, pretreatment is needed to increase the content of nutrients available to microalgal cells. In addition, an unbalanced nutrient profile in some agricultural wastewater may result in the low removal efficiency of nutrients. A previous study cultivated *Chlorella* sp. in dairy wastewater, but a low concentration of ammonia in the wastewater became a limiting factor in microalgae growth and nutrient assimilation (Lu *et al.*, 2016). Hence, under this situation, exogenous nutrients should be added into agricultural wastewater to balance the nutrient profile and improve the biomass yield.

20.3.2 Reactors for microalgae growth

To meet the requirement of practical application, reactors with various designs and structures for microalgae-based wastewater remediation have been developed. According to the shape and function, reactors for microalgae cultivation can be divided into two categories, open pond system and closed bioreactor.

20.3.2.1 Open pond system

In the open pond system, the culture environment of microalgae is directly exposed to the atmosphere. According to the economic analysis, among the bioreactors for microalgae cultivation, the open pond system has the advantage of low cost and easy operation (Costa and de Morais, 2013). Hence, if the open pond system is employed for microalgae-based agricultural wastewater remediation, the total cost can be controlled at a low level. However, due to the direct contact of the culture medium with air in the open pond system, airborne or wastewater-borne bacteria may grow fast in the agricultural wastewater, resulting in low biomass yield of microalgae (González-Fernández, Molinuevo-Salces, and García-González, 2011; Lam *et al.*, 2018). In addition to the competitive relationship, a cooperative relationship between microalgae and bacteria in agricultural wastewater is reported (Zhang *et al.*, 2020). It was discovered that in the treatment of manure, bacteria could accelerate the decomposition of organics and covert high-molecular-weight organics to low-molecular-weight organics, providing nutrients that can be easily assimilated by algal cells (Zhong *et al.*, 2021). Therefore, to use the open pond system for microalgae-based agricultural wastewater remediation, the interaction between microalgae and other microorganisms should be fully studied.

20.3.2.1 Closed bioreactor

Closed bioreactors, also known as photobioreactors, have a relatively complex structure and can provide a more stable and controllable environment for microalgae growth (Xu *et al.*, 2009). The materials used for closed bioreactors include glass and plastic. To increase the biomass yield of microalgae in agricultural wastewater, the closed bioreactors are usually equipped with light sources, circulation devices, CO_2 supply systems, and temperature control systems. According to

different design forms, closed reactors can be divided into pipeline photoreactors, flat-plate photoreactors, and column photoreactors.

In a real-world application, to select the appropriate reactor for microalgae-based agricultural waste treatment, a couple of factors should be taken into consideration. For example, the treatment cost of agricultural waste is an important concern. In some countries, the government provides financial support to the treatment of agricultural waste, so closed bioreactors with high investment cost will be affordable and can be widely used. In addition, biochemical properties of microalgae should be considered before the selection of reactors. Some microalgal species with strong attachment ability can adhere to the inner surface of a closed bioreactor. As a result, the process of cleaning the inner surface will be time-consuming and expensive. Under this situation, an open pond system has an advantage over the closed bioreactors for the cultivation of microalgae. Therefore, the actual situations can impact the selection of reactors for microalgae-based agricultural waste treatment.

20.3.3 Microalgae cultivation for agricultural waste treatment

Up to now, microalgae have been cultivated in swine manure, cattle manure, cane molasses, aquaculture effluent, alcohol fermentation wastewater, and some other agricultural wastes (Khalid *et al.*, 2019; Melo *et al.*, 2022). As shown in Table 20.1, a variety of microalgal species have been successfully employed to treat agricultural wastes and produce biomass. With the removal of nutrients in agricultural wastewater, algal biomass with high-value compounds is obtained. Therefore, microalgae could be widely applied in the treatment of various agricultural wastes. In our view, the successful application of microalgae in agricultural waste treatment can be attributed to two factors, namely, the high concentration of nutrients and the lack of toxic compounds in agricultural wastes. First, agricultural wastes are enriched with degradable organics, which can be efficiently utilized by microalgal cells. Accordingly, with a sufficient supply of nutrients, a high biomass yield of microalgae can be achieved. Second, compared with industrial wastewater and mining wastewater,

TABLE 20.1 Cultivation of microalgae in agricultural waste for nutrient recovery and biomass production.

Microalgal strain	Type of waste	Nutrient removal efficiency (%)			Biomass yield	Reference
		COD[a]	TN[b]	TP[c]		
Chlorella sp.	Dairy manure	27.4–38.4	75.7–82.5	62.5–74.7	1.47–1.71 g/L	(Wang *et al.*, 2010)
Chlorella vulgaris	Cattle farm wastewater	91.24–92.17	Ammonia: 83.16–94.27	90.98–94.41	1182.50 mg/L	(Lv *et al.*, 2018)
Chlorella sp.	Meat processing wastewater	43.91	49.48	54.45	1.400	(Lu *et al.*, 2015)
Scenedesmus sp.	Molasses wastewater	87.2	90.5	88.6	~2.287 g/L	(Ma *et al.*, 2017)
Haematococcus pluvialis and *Chromochloris zofingiensis*	Dairy wastewater	94–96	79–81	57–79	0.55–0.65 g/L	(Nishshanka *et al.*, 2022)
Haematococcus pluvialis	Bioethanol plant waste effluent		91.67	100	4.37 g/L	(Haque *et al.*, 2017)
Haematococcus pluvialis	Swine slurry	26	99	98		(Ledda *et al.*, 2016)
Chlorella vulgaris	Dairy wastewater	~16.44	~42.58	~21.79	1.16 g/L	(Lu *et al.*, 2016)
Chlorella sp.	Meat processing wastewater	29.52	50.94	44.95	1.538	(Lu *et al.*, 2015)
Chlorella sp.	Molasses wastewater	25.96	44.39	~31.25	4.215 g/L	(Yang, Li, and Wang, 2019)
Chlorella sp.	Meat processing wastewater	7.95	30.06	63.51	1.388	(Lu *et al.*, 2015)

agricultural wastes contain no toxic compounds, such as heavy metals and toxins (Baby Shaikh, Saifullah, and Rehman, 2018). Hence, there are much fewer factors that can hinder the microalgae growth in agricultural wastes. Due to the unique properties of agricultural waste, it can be regarded as a promising substrate for microalgae cultivation.

Although microalgae can be grown in many agricultural wastes, sometimes the nutrient removal efficiency and biomass yield are not high. Under these situations, microalgae-based agricultural waste treatment does not have an obvious economic advantage over traditional methods. In recent years, to further improve the nutrient removal efficiency and biomass yield of microalgae in agricultural waste treatment, some innovative technologies, such as digestion of wastewater, balance of nutrient profile, and co-culture of microalgae with bacteria, have been developed. For example, agricultural waste can be digested by controlled anaerobic fermentation, which can convert solid organics to volatile fatty acids. Compared with solid organics, volatile fatty acids can be assimilated by microalgal cells more efficiently. It should be noted that in this process, the anaerobic fermentation should be strictly controlled since excessive fermentation could result in the intensive emission of CH_4 and CO_2.

20.3.4 Utilization of algal biomass for downstream industry

Microalgae have extremely high application value in the field of biotechnology. They can be used as an important source of bio-fertilizer, biofeed, bioenergy, etc., and can also be used to produce high value-added bioactive substances, such as unsaturated fatty acids, pigments, polysaccharides, etc. Therefore, microalgae biomass can be exploited as a high-value substance for downstream industry.

20.3.4.1 Use of microalgae as bio-fertilizer

Microalgae can be used as bio-fertilizer to reduce the overuse of chemical fertilizer in agriculture (Uysal, Uysal, and Ekinci, 2015). Compared with chemical fertilizer, bio-fertilizer has advantages in the aspects of moisture maintaining and nutrient releasing. First, microalgae biomass added in soil can form a complex structure with the clay, preventing the moisture loss and maintaining the water content in soil (Lu and Xiao, 2022). Hence, microalgae are widely used in arid regions to prevent desertification. Second, inorganic nutrients contained in chemical fertilizer enter the soil rapidly and then penetrate soil into underground water. As a consequence, a high portion of nutrients in chemical fertilizer may not be assimilated by crops. By contrast, nutrients contained in microalgae-based fertilizer could be released slowly with the gradual decomposition of microalgae biomass. In this way, the utilization efficiency of nutrients in the microalgae-based fertilizer can be improved. In addition, microalgae cultivation is a carbon absorption process, while chemical fertilizer production is a carbon emission process. Considering the environmental protection and carbon neutrality, microalgae-based fertilizer has obvious advantage over chemical fertilizer.

20.3.4.2 Microalgae for bioenergy production

Microalgae biomass can be harvested from agricultural wastewater for biodiesel production. In such a technical route, organic carbon in agricultural waste can be converted to the carbon skeleton of esterified fatty acids in biodiesel. Since biodiesel has much higher value than agricultural waste, this technology can be regarded as a value-adding process. In a real-world application, to make the microalgae a suitable feedstock for biodiesel production, efforts should be devoted to the screening of microalgal strain and the selection of agricultural waste selection. First, oil-rich microalgal strains should be screened for biomass production, yielding biomass with high content of bio-oil. In recent years, with the fast development of genetic engineering technology, the expression of the genes that regulate oil biosynthesis in microalgal cells can be enhanced to improve the oil productivity (Muñoz *et al.*, 2021). Second, agricultural wastewater with a low ratio of N/C could be used to cultivate microalgae for bio-oil production. Previous studies have discovered that there is a close relation between N/C ratio and lipid synthesis. Generally, wastewater or culture medium with high N/C ratio could enhance the accumulation of protein in microalgae, while wastewater or culture medium with low N/C ratio is favorable to the synthesis of lipid in microalgae (Lourenço *et al.*, 1998). Hence, to select the appropriate agricultural waste for microalgae cultivation and bio-oil production, the N/C ratio should be taken into consideration. In a real-world application, the N/C ratio of wastewater can be adjusted to regulate the accumulation of lipid in microalgae. For example, in the previous study, ammonia-rich meat processing wastewater was mixed with dairy wastewater with a high content of organic carbon to improve the lipid yield in microalgae (Lu *et al.*, 2016).

20.3.4.3 Microalgae as an ingredient in animal feed

It has been discovered that microalgae are enriched with a variety of high-value compounds, which can positively impact the growth of animals (Zhou *et al.*, 2022). For example, *Haematococcus pluvialis* can synthesize astaxanthin, which

is a natural pigment with antioxidative properties. In the industry of animal breeding, microalgal astaxanthin has been proven to be a substance enhancing the growth of animals and reducing the mortality rate (Mularczyk, Michalak, and Marycz, 2020; Oslan *et al.*, 2021). Furthermore, the addition of microalgal astaxanthin in fish diet can promote the sedimentation of pigments in fish skin and change the color of fish (Li *et al.*, 2022). Therefore, microalgae with special properties can be added into animal feed.

In addition to the bioactive compounds, protein in microalgae merits the attentions of researchers in academic and industrial settings. In aquaculture, to provide fish and shrimp with sufficient protein, a high content of fish meal is added to the feed. However, the high price of fish meal increases the total cost of feed (Hodar *et al.*, 2020). By contrast, microalgae cultivated in agricultural wastewater, which can be obtained at very low cost, could be produced in a cost-saving way. According to previous studies, microalgae also contain high contents of protein and essential amino acids for animal growth. If microalgae biomass is employed to replace or partially replace fish meal, the total cost can be reduced accordingly.

To use microalgae for fish meal replacement in fish diet, some problems should be solved in advance. First, different from fish meal, microalgae have a cell wall, which cannot be efficiently digested by some carnivorous fish. Consequently, the protein contained in the microalgae biomass may not be effectively utilized by carnivorous fish. To overcome this problem, microalgae biomass can be fermented to promote the decomposition of the cell wall. Furthermore, an enzyme product can be employed to accelerate the decomposition rate of the cell wall of microalgae. Via damaging the structure of the cell wall, nutrients contained in microalgae can be released and then be utilized by animals efficiently. Second, the palatability of microalgae biomass is much worse than that of fish meal. In the practical application, it was discovered that a fish diet with high inclusion of microalgae biomass was much less attractive to carnivorous fish. Therefore, to avoid the negative effect of poor palatability of microalgae biomass on fish growth, appetite-inducing substances should be added to the fish diet as well.

20.4 Solid-state fermentation of crop waste by high-value microorganisms

In agriculture, there are two major types of crop wastes, namely crop straw and crop bran. Crop straw is generated during the crop harvesting and crop bran is a byproduct of crop processing. Solid-state fermentation of crop waste refers to the process of cultivating microorganisms on solid crop waste without the presence of free liquid (Chilakamarry *et al.*, 2022). By the end of solid-state fermentation, a portion of crop waste can be degraded and high-value bio-products can be obtained. Compared with some traditional methods, such as crop straw burning and crop straw landfilling, solid-state fermentation of crop waste can promote the valorization of agricultural waste and have no negative effect on the environment. Therefore, solid-state fermentation is regarded as an important method for crop waste treatment.

In this section, mechanisms of crop waste treatment by solid-state fermentation are introduced. In addition, high-value microorganisms, which have been successfully used for solid-state fermentation, are discussed. By the end of this section, an in-depth discussion of the practical application of fermented crop waste as animal feed is provided.

20.4.1 Mechanisms of crop waste treatment by the solid-state fermentation

Solid-state fermentation of crop waste mainly uses microorganisms to perform biotransformation on solid substrates of crop waste. During this process, microorganisms inoculated on crop waste degrade high-molecular-weight organics, such as cellulose, hemicellulose, and lignin, in straw into low-molecular-weight organics, such as monosaccharides (glucose, xylose, etc.) and metabolites (organic acids, alcohols, etc.). In the decomposition process, the extracellular enzymes, such as hemicellulase, cellulase, and ligninase, secreted by microorganisms play an important role (Amadi *et al.*, 2020; Leite *et al.*, 2021). Those low-molecular-weight organics can be further used by microorganisms to synthesize the microbial biomass and support the microbial metabolisms, thereby achieving the biodegradation and transformation of crop waste.

Main processes of solid-state fermentation for crop waste treatment have been fully documented by previous studies. In general, there are three major steps, namely the attachment and growth of microorganisms, degradation and transformation of crop waste, and generation and accumulation of metabolites.

(1) In the early stage of the solid-state fermentation of crop waste, microorganisms are attached on the surface of crop waste and adapted to the new environment gradually. As the solid-state fermentation proceeds, microorganisms inoculated on crop waste form biofilms, and the biofilms gradually thicken with the growth and reproduction of microbial cells. In this process, driven by the extracellular enzymes secreted by microorganisms, decomposition of crop waste starts.

(2) The degradation of crop waste mainly depends on the extracellular enzymes secreted by microorganisms. These enzymes can accelerate the components, such as cellulose, hemicellulose, and lignin, contained in crop waste and convert high-molecular-weight organics to low-molecular-weight organics. For example, cellulase can decompose cellulose into glucose, hemicellulase can decompose hemicellulose into xylose, and ligninase can decompose lignin into phenolic compounds (Leite *et al.*, 2021; de Oliveira Júnior *et al.*, 2022). The low-molecular-weight organics can be assimilated by microbial cells for metabolism.

(3) During the process of crop waste degradation and conversion, a variety of metabolites, such as sugar, organic acids, alcohols, gases, and so on, can be produced by microorganisms. These metabolites include organic acids, alcohols, gases, etc. Among them, sugar, organic acids, and alcohols can be assimilated by microorganisms as carbon sources and energy sources to support cell growth and reproduction; gases, such as methane, can be collected and used as bioenergy. As a consequence, by the end of the solid-state fermentation, microbial biomass with high-value components and high-quality bio-products can be obtained.

To create a comfortable environment for solid-state fermentation, a couple of factors with important effects on the fermentation process should be taken into consideration. First, microbial species and quantity should be identified based on the goal of solid-state fermentation. Different types of microorganisms have very different degradation capabilities and metabolites. Furthermore, the inoculation amount of microorganism on crop waste could determine the degradation rate and the fermentation period. Therefore, selecting the appropriate species and quantity of microorganisms for sold-state fermentation is of great significance in improving the treatment efficiency and product quality of crop waste. Second, fermentation conditions should be optimized to improve the treatment performance of crop waste. Normally, conditions that should be taken into consideration include fermentation temperature, pH value, oxygen content, and humidity (Zhang *et al.*, 2020). These conditions can impact the growth and metabolism of microorganisms, further influencing the decomposition rate of crop waste. For instance, a suitable temperature (20−35°C) can increase the growth rate of microorganisms, while excessively high temperature hinders the growth of microorganisms and even causes the death of microbial cells. Therefore, the optimal fermentation conditions should be identified according to the microbial species and properties of crop waste. Third, types and properties of crop waste could partially determine the efficiency and product quality of the solid-state fermentation. In most cases, the microbial species and the fermentation conditions should be determined according to the types and properties of crop waste. For example, corn straw contains rich cellulose and hemicellulose, while rice straw contains more lignin. In a real-world application, to treat corn straw, microorganisms with the ability of secreting cellulase and hemicellulase should be selected for the solid-state fermentation.

20.4.2 Solid-state fermentation by high-value microorganisms

In nature, there are numerous microorganisms that can promote the decomposition of crop waste via solid-state fermentation. However, in the practical application, only a few microbial species are used for solid-state fermentation, playing a key role in the degradation and transformation of crop waste. The following are common types of microorganisms in the solid-state fermentation of crop waste.

Lactic acid bacteria are a commonly used microorganism that could degrade organics in crop waste and promote fermentation (Méndez *et al.*, 2021). It was reported that lactic acid bacteria could quickly decompose carbohydrates in crop waste into organic acids (Spaggiari *et al.*, 2020). It should be noted that the lactic acid bacteria have beneficial effects on animals' health (Hernández-González *et al.*, 2021). If the crop straw fermented by probiotics, such as lactic acid bacteria and *Bacillus subtilis,* are used as animal feed or added to an animal diet, the growth of animals will be positively impacted. Some cellulolytic bacteria perform well in the decomposition of cellulose via secreting cellulases and yield cellobiose and glucose, which can be digested by animals efficiently. In addition to bacteria, some molds could be employed to accelerate the decomposition of crop waste. For example, *Trichoderma reesei* and white rot fungi have been widely cultivated for the solid-state fermentation of crop straw (Lodha, Pawar, and Rathod, 2020; Yan *et al.*, 2022). In recent years, with the fast development genetic technology, genetically modified microorganisms with special functions are emerging into the limelight for the solid-state fermentation of crop waste.

To select the appropriate microbial species for the solid-state fermentation of crop waste, a couple of factors, such as the properties of crop waste, fermentation environment, and requirement on the fermentation product, should be taken into consideration. First, the properties of crop waste should be analyzed before the selection of microbial species. For instance, to degrade crop waste with a high content of cellulose, cellulolytic bacteria should be selected as one of the microbial species for solid-state fermentation. In this way, with the assistance of cellulase, the decomposition of crop waste will be accelerated. Second, fermentation environment, which partially determines the performance of microorganisms in solid-state fermentation, should be fully studied. For example, if the temperature of the fermentation environment is low,

then microbial species with a high tolerance to the cold environment should be employed for the crop waste treatment. By contrast, if the fermentation is conducted under a hot environment, thermophilic microorganisms should be selected as the appropriate microbial species for the solid-state fermentation. Third, the requirement on the fermentation product should be taken into consideration. For example, if the downstream industry plans to use the fermented crop waste as animal feed, probiotics could be employed to enhance the positive effects of fermented crop waste on animals' health.

20.4.3 Application of fermented crop waste as animal feed

Crop waste solid-state fermentation technology has broad application prospects. On one hand, the application of this technology can lower the risk of environmental pollution, further promoting sustainable agricultural development. On the other hand, the value of crop waste can be improved after solid-state fermentation.

Up to now, fermented crop waste has been used as fertilizer and animal feed in agricultural activities (Bibi *et al.*, 2022; Eliopoulos *et al.*, 2022; Wang *et al.*, 2023). To our knowledge, animal feed with a high market price is a much better choice for the application of fermented crop waste in downstream industry. In most cases, crop wastes, such as wheat straw, rice straw, and wheat bran, can be obtained at low cost. Sometimes, the government even provides financial support to the organizations doing business in the field of crop waste recycling. Therefore, the replacement of traditional animal feed with fermented crop waste can reduce the cost of feeding animals and improve the health status of animals. In addition, by the end of fermentation process, with the growth of probiotics, the total number of probiotics in the crop waste will reach the peak value. Accordingly, with the addition of the fermented crop waste into animal feed, probiotics will positively impact the growth and health status of animals (Bhogoju and Nahashon, 2022). Last but not the least, during the fermentation process, cellulose, hemicellulose, and lignin are converted to low-molecular-weight organics, which could be efficiently assimilated by animals. Due to the advantages in the total cost, beneficial functions, and nutrient digestibility, solid-state fermentation can be regarded as an applicable method to pretreat the agricultural waste for animal feed production.

20.5 Production of hydrogen gas by using agricultural waste

With the increasing severity of the global energy crisis and environmental problems, more and more researchers in academia and industry are focusing on the utilization of hydrogen as a clean and renewable energy (Woon *et al.*, 2023). Hydrogen has no greenhouse gas emission, showing great advantage over fossil fuel. At present, hydrogen is mainly obtained by water electrolysis, but this process is energy-intensive. As an emerging energy technology, microbial fermentation to produce hydrogen has attracted much attention due to its unique advantages and potential. In recent years, researchers have achieved great progress in the application of agricultural waste for hydrogen production, providing a low-cost and innovative way for sustainable development (Zheng *et al.*, 2022). This section will give a detailed introduction to the principles, technologies, applications, and prospects of microbial fermentation to treat agricultural waste for hydrogen production.

20.5.1 Microbes for hydrogen gas production

Microbial fermentation to produce hydrogen is a process in which specific microorganisms produce hydrogen by metabolizing organic matter under anaerobic or microaerobic conditions. In general, the process of microorganism-based hydrogen production can be classified into two categories, namely the photosynthesis for hydrogen production and dark fermentation for hydrogen production (D'Silva *et al.*, 2023): (1) Photosynthesis-based hydrogen production is a process through which a microorganism turns water or organic matter into hydrogen; (2) Dark fermentation is a complex process that employs bacteria to convert organic substrates into biohydrogen in the absence of light and oxygen. The technology of hydrogen production by microbial fermentation mainly includes species screening, fermentation condition optimization, and reactor design.

20.5.1.1 Screening of strains

Screening of microbial strains with efficient hydrogen production ability is the key to the practical application of microorganism-based hydrogen production. At present, a variety of microorganisms with hydrogen production ability have been isolated and successfully used in the industry. *Anabaena, Synechococcus,* and *Oscillatoria* sp. have been studied for photoproduction of hydrogen, while *Clostridium, Desulfovibrio,* and *Enterobacter* sp. are commonly used for dark fermentation for hydrogen production (Sudheer, Chauhan, and Velramar, 2020; Zayadan *et al.*, 2021). In recent years, with

the identification of the genes regulating the hydrogen production in microbial cells, genetic modification techniques can be adopted to improve hydrogen production efficiency.

20.5.1.2 Fermentation conditions

Dark fermentation is a fermentation process that does not require light energy (Sarangi and Nanda, 2020). It uses the multi-enzyme system of bacterial groups to convert organic matter into biohydrogen through anaerobic conversion. The dark fermentation reaction does not rely on light energy, so it can be carried out in daytime and at night. During the dark fermentation process, microorganisms decompose organic matter into simple hydrocarbons with the assistance of specific enzymes and then further convert these organic compounds into hydrogen. The dark fermentation process is impacted by a couple of conditions, such as temperature, pH value, substrate concentration, inoculation amount, etc. It should be noted that since the dark fermentation does not require illumination, light quality is not considered in the optimization of dark fermentation of agricultural waste for hydrogen production.

20.5.1.3 Reactor design

The reactor is the core equipment of microbial fermentation for hydrogen production in agricultural waste. A well-designed reactor could not only improve mass transfer efficiency and reduce energy consumption but also reduce the carbon emissions and make the fermentation process eco-friendly. At present, reactors that are used for microorganism-based hydrogen production mainly include batch reactors, continuous flow reactors, and biofilm reactors (Mikheeva *et al.*, 2022; Safari, Tondro, and Zilouei, 2022; Santiago *et al.*, 2020). Since these reactors have their own advantages and weaknesses, they should be selected according to specific conditions in the practical applications. In general, factors that can determine the reactor design include the investment cost, substrate properties, fermentation conditions, and so on.

20.5.2 Production of hydrogen gas by the fermentation of agricultural waste

The technical processes of agricultural waste fermentation hydrogen include the following steps: collection and transportation of agricultural waste, pretreatment of agricultural waste, fermentation, collection of hydrogen, and treatment of fermented agricultural waste. First, various types of agricultural wastes, such as crop straw, rice shells, livestock and poultry manure, etc., should be collected and transported to the destination in a proper way. Second, the pretreatment, such as crushing, compressing, and dehydrating, should be conducted to make agricultural waste suitable for the fermentation. Third, microorganisms are inoculated in the agricultural waste and the fermentation for hydrogen production is started under the optimal conditions. At this step, measures should be taken to control the fermentation conditions. Fourth, hydrogen should be collected in an efficient and safe way and stored properly. Since hydrogen is a dangerous gas, which may cause serious accidents, the process of hydrogen collection should be managed according to the regulations strictly. Fifth, by the end of fermentation, the residual of agricultural waste should be treated to reduce its potential threat to the environment.

In recent years, with the increasing severity of the global energy crisis and environmental problems, people's demand for eco-friendly and renewable energy is increasing rapidly. Under this situation, microorganism-based hydrogen production in agricultural waste, as a potential technology integrating clean energy production and agricultural waste treatment, will be more widely used and developed in the future.

20.6 Assessment of the greenhouse gas emission

Greenhouse gas emission, which accelerates the greenhouse effect on the Earth, is increasing gradually in agriculture. For example, with the fast development of pig farming and processing industries, a large volume of wastewater with a high content of organic carbon is generated. In the pig farming industry, piggery manure, of which the concentration of TOC could reach around 15,000 mg/L, is produced continuously (Sepúlveda-Muñoz *et al.*, 2020). If traditional treatment technologies, such as chemical oxidation based on Fenton reaction, aerobic digestion, and anaerobic fermentation, are adopted to remove organic carbon in piggery wastewater, intensive CO_2 emission will occur. Although compared with fossil energy utilization, agricultural activity produces much less greenhouse gases, efforts are still needed to lower the carbon footprint of agriculture and promote the development of sustainable agriculture. Therefore, in this section, greenhouse gas emission caused by the treatment of agricultural waste is discussed, and innovative methods to lower the greenhouse gas emission are introduced.

20.6.1 Carbon sequestration by microalgae growth in agricultural waste

As discussed in Section 3.3, microalgae cultivation has been intensively applied as a promising and innovative technology for nutrient recovery in agricultural waste. In fact, microalgae cultivation performs well in carbon sequestration by both photosynthesis and heterotrophic metabolism.

Microalgal cells can capture atmospheric CO_2 by photosynthesis, further lowering the carbon footprint of agricultural waste treatment. In addition, microalgal cells grown in agricultural waste could effectively fix the CO_2 released by wastewater-borne bacteria or fungi. As a consequence, CO_2 released from agricultural waste can be lowered. Hopefully, with the increase of microalgae concentration in agricultural wastewater, more CO_2 can be fixed and converted to microalgae biomass.

In addition to photosynthesis, heterotrophic metabolism of microalgae could contribute to the reduction of CO_2 emission caused by agricultural wastewater. Via heterotrophic metabolism, organic carbon can be assimilated by microalgal cells and utilized for biomass synthesis. Otherwise, if traditional technologies, such as advanced oxidation, anaerobic fermentation, and aerobic digestion, are applied for agricultural wastewater treatment, a large amount of CO_2 will be released. Therefore, the process of converting organic carbon in wastewater to microalgae biomass can be regarded as carbon sequestration. According to previous studies, sugars and volatile fatty acids, which are common carbon formats in agricultural wastewater, can be efficiently assimilated by microalgal cells by heterotrophic metabolism.

For example, a certain type of agricultural wastewater, in which the concentration of TOC is set as 4,000 mg/L, is sent to a wastewater treatment plant (WWTP). If option 1 based on traditional treatment technology is applied for wastewater remediation, CO_2 emission will reach 11,733 mg CO_2/L wastewater when the removal efficiency of TOC is 80%. The CO_2 emission under this situation is equal to 5.875 L CO_2/L wastewater. If option 2 based on the microalgae cultivation is applied for wastewater remediation, CO_2 emission of the wastewater treatment process can be remarkably reduced with the accumulation of microalgae biomass. Herein, the removal efficiency of TOC is set as 80%, and the biomass yield of microalgae containing 55% carbon element is set as 4 g/L. Accordingly, in the wastewater, 2,200 mg carbon in 1 L wastewater is converted to microalgae biomass, resulting in low CO_2 emission (3,667 mg CO_2/L wastewater), which is equal to 1.836 L CO_2/L wastewater. Therefore, in this case, compared to the traditional treatment technology, microalgae cultivation could dramatically reduce the carbon footprint of wastewater treatment.

The harvested microalgae biomass can be further utilized to produce biofuel, which has been regarded as a green energy source. In the coming future, with the wide use of microalgae-based biofuel, intensive CO_2 emission caused by fossil fuel can be reduced. Particularly, the profits of producing microalgae-based biofuel can cover the cost of agricultural waste treatment. Therefore, this is a win-win strategy, which not only controls the pollution caused by agricultural waste, but also produces eco-friendly energy.

20.6.2 Replacement of crop straw burning by solid-state fermentation

In the past, crop straw was burned and the ash was returned to the field. However, this process not only produces a large amount of CO_2 but also creates few profits. Additionally, the ash produced during the burning process could cause air pollution. Although solid-state fermentation is also a CO_2-releasing reaction, the carbon emission of microorganisms in fermentation is much less intensive than the burning process. Therefore, to reduce the carbon emission of crop straw treatment and make the crop straw treatment a value-adding process, solid-state fermentation could be adopted. Unfortunately, up to now, few studies have comprehensively compared the carbon emission of crop waste burning process and solid-state fermentation. In the view of the present authors, in the coming future, experiments should be conducted to clearly identify the fate of the carbon element during the burning process and solid-state fermentation of crop waste.

20.6.3 Hydrogen gas as an eco-friendly energy source in the future

Although the production of hydrogen by culturing microorganisms in agricultural waste could not directly reduce the carbon emission, the wide use of hydrogen as an energy source is important to the upgrading of energy industry and the reduction of greenhouse gas emission.

Higher heating value (HHV), which is defined as the amount of heat released by the unit mass or volume of fuel, has been used to assess the quality of energy source. According to previous studies, the HHV of hydrogen (H_2) is 141.9 MJ/kg, while that of methane (CH_4) is only 55.6 MJ/kg. Accordingly, through complete combustion, 1 kg hydrogen could produce 141.9 MJ thermal energy, while 1 kg methane could only produce 55.6 MJ thermal energy. Particularly, the complete combustion of 1 kg hydrogen produces no greenhouse gas, while the complete combustion of 1 kg methane

yields 2.75 kg CO_2. Therefore, in terms of HHV and greenhouse gas emission, hydrogen is much better than methane as an energy source.

It should be noted that the energy input of the fermentation of agricultural waste for hydrogen production is much lower than that of the water electrolysis. Therefore, fermentation of agricultural waste for hydrogen production not only has environmental benefits but also has economic benefits.

20.7 Conclusion and future prospects

Although innovative technologies have been developed to promote the conversion of agricultural waste to high-value biomass and biofuel, the limitations of the innovative technologies should not be neglected. In the view of the present authors, with the improvement of the technologies introduced by this book chapter, agricultural waste will be intensively used as the feedstock for the production of biomass and biofuel. In general, limitations that hinder the wide application of agricultural waste for biomass and biofuel include the lack of government support, inconsistent steps toward carbon neutrality, and the weakness of current technologies. To promote the sustainable development of agriculture, these limitations should be overcome in the future.

First, in most cases, companies that work on the valorization of agricultural waste could not receive enough support from the government. To apply these innovative technologies, high investment and well-trained labor are needed. For example, to apply the microalgae for agricultural wastewater remediation, companies should establish microalgae cultivation ponds and train technicians working on microalgae inoculation and harvesting. The high cost of applying these innovative technologies may increase the financial burden of the companies. Under this situation, financial support from the government is important and helpful to those companies (Choi and Park, 2023). On one hand, the government's support could reduce the risks of conducting technological innovations of the companies and accelerate the practical application of innovative technologies. On the other hand, government support will encourage more and more companies engaging into the technological innovations related to the agricultural waste. In this way, progress will be achieved in the research of agricultural waste treatment.

Second, in the world, countries have inconsistent steps toward carbon neutrality, so the innovative technologies for agricultural waste treatment may not be widely adopted. At present, many developed countries show great interest in the target of carbon neutrality, while some undeveloped countries do not set a clear target to achieve carbon neutrality (Chen *et al.*, 2022; Xu *et al.*, 2022). By contrast, the volume of agricultural production in many undeveloped countries is huge. As a result, even if there are many innovative technologies that can reduce the carbon emission of agricultural waste, they may not be widely applied by those countries without the goal of carbon neutrality. To solve this problem, international organizations should be established to promote the sustainable treatment of agricultural waste. For example, strict regulation should be made by international organizations to inhibit the burning of crop waste. Only in this way could the countries devote more efforts to applying eco-friendly technologies to treat the agricultural waste.

Third, although the innovative technologies introduced by this chapter have made certain progress and achievements, they still face some challenges and problems in practical applications. The performance of these technologies in laboratory research is excellent, but it may not be directly applied in industry. For example, in laboratory research, some microbial species have been screened to produce hydrogen in agricultural waste. Through optimizing the fermentation parameters, hydrogen productivity has been improved remarkably. However, in the practical application, this technology is rarely used because the transportation of hydrogen is complex. Furthermore, most countries have not established an industry a with high consumption of hydrogen even though hydrogen has been proven to be an eco-friendly energy source. Last, the large area occupation of the biohydrogen production system and the relatively low hydrogen production rate seriously limit its promotion and application in large-scale applications. Therefore, due to the lack of market demand in the downstream industry and the complexity of reactors, hydrogen produced during the agricultural waste treatment could not truly bring profits to the companies applying innovative technologies for agricultural waste treatment. To solve this problem, a complete industrial chain, which can connect agricultural waste treatment and the downstream industry, should be established. In the view of the present authors, to promote the wide application of microalgae-based agricultural wastewater treatment, downstream industry that can use microalgae biomass as feedstock should be developed in advance. Also, it is necessary to further strengthen research and technological innovation to overcome the technical challenges.

In the coming future, via solving the aforementioned problems, these innovative technologies that convert agricultural waste to high-value products will be widely applied to achieve sustainable development and the target of carbon neutrality.

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Chapter 21

Vermicomposting for waste decomposition and soil health improvement: Risk and challenges

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Chapter Outline

21.1. Introduction 349
21.2. Vermicomposting process 351
22.3. Benefits of vermicomposting 357
21.4. Risks associated with vermicomposting 358
21.5. Challenges in vermicomposting 360
21.6. Economic considerations 362
21.7. Strategies for mitigating risks and overcoming challenges 363
21.8. Future directions and opportunities 365
21.9. Conclusion 367
References 367

21.1 Introduction

Vermicomposting provides a distinctive and eco-friendly approach to manage organic waste. This approach utilizes the inherent decomposition ability of earthworms, particularly red wigglers (*Eisenia fetida*), which are recognized for their fast reproduction and effective composting skills (Garg and Gupta, 2011). The key to a prosperous vermicomposting system is creating an appropriate environment for the worms. This entails creating a foundation layer by utilizing shredded paper products, cardboard, or coconut coir. This feature guarantees that the environment maintains an optimal level of moisture, which is essential for the well-being and activity of the worms (Pirsaheb, Khosravi, and Sharafi, 2013). The selected materials provide enough airflow, preventing the development of anaerobic conditions that are harmful to the worms. The bedding serves as an easily accessible source of food for the worms as they establish themselves in the system. Vegetable peels, fruit cores, and eggshells from the kitchen are transformed into useful resources when used in a vermicomposting system. The worms rapidly ingest these organic materials and convert them into a nutrient-rich biofertilizer called vermicompost (Bhat *et al.*, 2018). This final product contains a rich assortment of vital plant nutrients, such as nitrogen, phosphorus, potassium, and calcium (Sharma and Garg, 2018). Figure 21.1 shows the basic process of vermicomposting.

Conventional waste management methods frequently utilize landfills, resulting in environmental issues such as the release of methane, a powerful greenhouse gas, and the poisoning of groundwater by leachate (heavy metals, pesticides,

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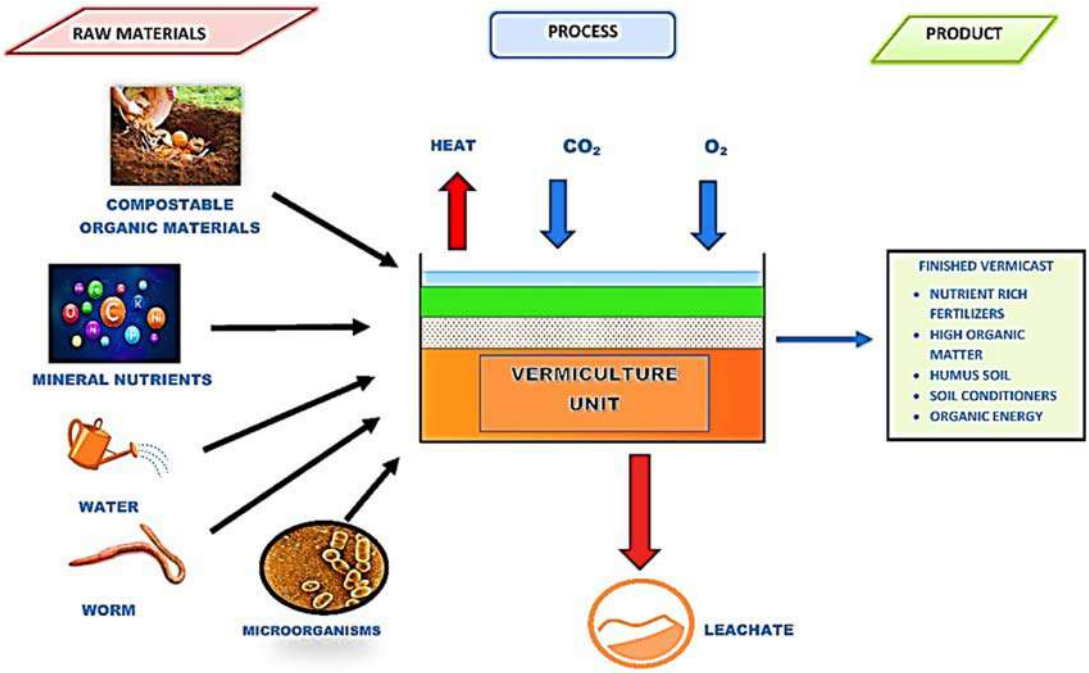


FIGURE 21.1 **Process of vermicomposting.**

etc.) (Ghosh *et al.*, 2023; Roy *et al.*, 2024, 2023; Moulick *et al.*, 2024). Vermicomposting provides an enclosed system that redirects organic waste away from landfills and converts it into a valuable resource. Commonly overlooked kitchen waste such as vegetable peels, fruit cores, eggshells, and coffee grounds provide nourishment for earthworms. These diligent decomposers efficiently break down organic matter, resulting in a large reduction in waste volume and redirecting it away from landfills. Research has indicated that vermicomposting has the ability to redirect as much as 80% of food waste generated by households, thus making a substantial impact on trash reduction initiatives (Sharma and Garg, 2019).

Vermicomposting provides a sustainable solution for two major issues: the management of waste and degradation of the soil. With the increase in urbanization and industrialization, there is an equivalent increase in the production of organic waste. Vermicompost improves soil structure, aeration, and water retention capacity, which is beneficial for soil health (Karmakar *et al.*, 2015). The earthworms generate humus, a nutrient-rich substance containing nitrogen, phosphorus, potassium, and trace elements that are vital for the growth of plants (Chatterjee, Debnath, and Mishra, 2020). In addition, vermicompost delivers advantageous microorganisms into the soil, which have a vital function in the cycling of nutrients, suppression of diseases, and decomposition of organic matter. Better microbial activity not only increases soil fertility and greater nutrient availability but also strengthens plant resistance to pests and illnesses, thus strengthening sustainability in crop production (Majumdar *et al.*, 2024, 2023; Deb *et al.*, 2023; Pattnaik *et al.*, 2023; Pathma and Sakthivel, 2012).

Vermicomposting has relevance not just in terms of environmental advantages, but also in terms of economic and social dimensions. It offers an inexpensive and simple solution that may be used in various environments, ranging from rural agricultural areas to metropolitan homes. Its accessibility makes it a great tool for waste management programs and sustainable farming practices in underdeveloped locations with limited resources for advanced waste treatment and soil additions (Thiruneelakandan and Subbulakshmi, 2014). Vermicomposting can be easily incorporated into other sustainable agriculture and waste management activities. Organic farming relies on it as a fundamental element to sustain soil health, eliminating the need for synthetic fertilizers and pesticides. Vermicast, which is rich in nutrients, promotes crop yields and enhances the quality of agricultural produce, leading to higher prices in markets (Kaur, 2020).

Vermicomposting can be included in urban environments as a component of a comprehensive plan to achieve zero waste communities. Household and community-scale vermicomposting units can alleviate the strain on municipal waste management systems, lower transportation costs and emissions linked to garbage collection, and promote local involvement in sustainability activities. Schools, community gardens, and businesses can implement vermicomposting to effectively handle their organic waste on their premises, thus transforming a potential waste issue into a valuable resource (Sim and Wu, 2010).

Furthermore, vermicomposting can enhance livestock farming by efficiently managing manure. Instead of accumulating or dispersing untreated animal waste, which can result in the loss of nutrients and pollution, incorporating vermiculture systems can stabilize nutrients, decrease the presence of harmful microorganisms, and provide top-notch compost that can be utilized to enhance pastures and agricultural areas (Ambasta and Kumari, 2013).

Vermicomposting is in line with multiple Sustainable Development Goals (SDGs) established by the United Nations. More precisely, it has an impact on:

SDG 2: Zero Hunger: Vermicomposting enhances soil health and fertility, hence promoting higher agricultural productivity, which is crucial for ensuring food security.
SDG 12: Responsible Consumption and Production: Vermicomposting facilitates the sustainable handling of organic waste, thereby mitigating the environmental consequences of waste disposal.

Vermicomposting contributes to climate change mitigation by sequestering carbon in the soil and reducing greenhouse gas emissions from landfills, in accordance with SDG 13: Climate Action. Vermicomposting's integration into sustainable development frameworks highlights its significance as a versatile solution to environmental and agricultural concerns.

In this chapter, our objective is to present a holistic assessment of the possibilities and challenges of vermicomposting from a sustainable agro-environmental prospective.

21.2 Vermicomposting process

21.2.1 Role of earthworms in decomposition

Earthworms are essential for the decomposition of organic materials. They operate as natural bioreactors, facilitating the breakdown of complex organic compounds into simpler ones. The particular species employed in vermicomposting, such as red wigglers (*E. fetida*), European nightcrawlers (*Eisenia hortensis*), and African nightcrawlers (*Eudrilus eugeniae*), are chosen for their effectiveness in decomposing organic waste and their capacity to adapt to composting conditions (Ansari and Ismail, 2012).

When organic matter is added to a vermicomposting system, earthworms ingest it and initiate the process of digestion. During the passage through the worm's digestive tract, the material undergoes fragmentation and is thoroughly combined with digestive enzymes and helpful microbes. This process not only mechanically disintegrates the material but also undergoes a chemical conversion, resulting in the production of nutrient-rich castings, known as vermicast (Bhat *et al.*, 2018). Vermicast is an extremely important final product that has a high concentration of humus, nutrients, and beneficial microorganisms (Domínguez, 2018).

The earthworm's gut has a distinct microenvironment that fosters a symbiotic relationship between the worms and microorganisms. Microorganisms, such as bacteria, fungus, and protozoa, are essential for decomposing organic matter. They break down the complex molecules into simpler forms that plants can easily use (Gómez-Brandón and Domínguez, 2014). The earthworm's locomotion within the substrate also facilitates aeration and drainage, thus augmenting the composting process by sustaining aerobic conditions that are crucial for effective decomposition (Huang *et al.*, 2014).

21.2.2 Key components of a vermicomposting system

Earthworms, commonly referred to as "ecosystem engineers," have a substantial influence on the structure and richness of soil. Their excavation efforts generate tunnels that promote the aeration and penetration of water in the soil, hence enhancing its texture and drainage (Lavelle, 1988). Vermicomposting utilizes these innate activities to expedite the breakdown of organic substances. Earthworms ingest organic debris and soil, breaking it down through digestion to obtain nutrients. Their digestive mechanism enhances the substance by incorporating helpful microbes and humus. The vermicast that is produced includes a greater abundance of nutrients, including nitrogen, phosphate, and potassium, in comparison to the initial organic material (Bhadauria and Saxena, 2010).

Additionally, earthworms have a crucial function in the process of nutrient cycling. By decomposing organic matter, they liberate nutrients that are easily accessible to plants. The bioavailability of nutrients improves both plant growth and soil fertility (Syers and Springett, 1984). Earthworms' ongoing activity also enhances the development of durable soil aggregates, hence enhancing soil structure and mitigating erosion (Medina-Sauza *et al.*, 2019).

21.2.3 Worm bins

21.2.3.1 Design and size

Worm bins are available in a range of forms, such as stackable trays, flow-through systems, and basic single-layer containers. The selection of a bin is contingent on the magnitude of the undertaking and the availability of space. Optimal bin design guarantees sufficient air circulation and moisture retention, both of which are essential for the well-being and activity of worms (Declaro, 2018). Bins can be constructed using plastic, wood, or metal. Plastic bins are characterized by their lightweight and durable nature, and yet they necessitate increased ventilation. Wooden dumpsters are porous but can deteriorate with time. Metal bins are durable but susceptible to corrosion (Manaf *et al.*, 2009).

21.2.3.2 Modular tray systems

These systems consist of many trays that are vertically stacked. Once the worms have completed the decomposition of the material in one tray, they move on to the next tray containing new feedstock. There is optimal usage of space, convenient extraction of vermicast from lower trays, and uninterrupted processing as worms move upward. Regular monitoring is necessary to guarantee appropriate migration and prevent overpopulation in trays (Manyuchi *et al.*, 2013).

21.2.3.3 Flow-through systems

These systems operate by continuously moving organic material from the top while collecting finished vermicast from the bottom. Typically, they incorporate a mesh or grate that lets the processed substance pass through while keeping the worms inside. The vermicast can be processed efficiently and separated easily, making it ideal for large-scale operations. This process necessitates meticulous control of the materials used as feedstock and frequent removal of the fully decomposed compost to avoid blockages (Lin *et al.*, 2021).

21.2.3.4 Monolayer containers

These are uncomplicated receptacles or containers in which organic matter is deposited and undergoes processing in a single layer. These containers can include plastic tubs, wooden boxes, or other receptacles that have ventilation apertures. They are economical, simple to establish, and appropriate for small-scale or domestic utilization. This process involves regular maintenance to ensure enough aeration and moisture levels, as well as physical separation of worms from the completed compost (Sahoo *et al.*, 2023).

21.2.4 Material used for bedding

Bedding materials commonly used include shredded newspaper, cardboard, peat moss, coconut coir, and aged compost. These materials serve as a habitat for the worms and contribute to the maintenance of moisture and aeration (Manaf *et al.*, 2009).

Preparation and maintenance: It is recommended to dampen the bedding until it reaches the texture of a sponge that has been wrung out. Over a period of time, bedding materials undergo decomposition and require replenishment in order to sustain an ideal habitat for the worms (Getinet, Hailu, and Birhanu, 2021).

21.2.5 Organic feedstock

Organic feedstock refers to raw materials that are derived from organic sources, such as plants or animals, and that are used as a basis for producing various products. Acceptable feedstock options encompass fruit and vegetable scraps, coffee grounds, tea bags, crushed eggshells, and garden trash. These materials have a high nutritional content and break down easily. Preparation and feeding: The feedstock should be cut into small pieces to speed up the process of breakdown. Establishing a regular feeding plan, usually on a weekly or biweekly basis, is crucial for ensuring consistent worm activity and compost generation (Ndegwa, Thompson, and Das, 2000).

21.2.6 Environmental conditions

The ideal temperature range for vermicomposting is between 15 and 25°C (59–77°F). Extreme temperatures exceeding 30°C (86°F) or falling below 10°C (50°F) can cause significant strain or even death to the worms (Kristiana *et al.*, 2005). The optimal moisture level for the bin should be between 70 and 90%. The adequacy of the moisture level can be determined by applying pressure on the mattress and observing the release of a few drops of water. Excessive moisture can result in oxygen-deprived surroundings and unpleasant smells, while dry circumstances can impede the breakdown of organic matter and the activity of worms.

Adequate aeration is essential to avoid the occurrence of anaerobic conditions. Regularly rotating the bedding or ensuring that the bin design facilitates adequate air circulation helps to maintain aerobic conditions.

21.2.6.1 Best practices for maintaining optimal environmental conditions

21.2.6.1.1 Thermal regulation. The use of insulating materials or placing the bin in a temperature-controlled environment assists in maintaining ideal temperatures. Shade and ventilation are essential in hot climates to prevent overheating of the bin. Proper shade and sufficient ventilation help maintain a cooler temperature inside the bin. To sustain worm activity in cold climates, it is advisable to utilize heating pads or relocate the bin indoors during the winter season (Frederickson and Howell, 2003).

21.2.6.1.2 Regulation of moisture. Continuously monitor moisture levels and supplement with water as needed. Employing a spray bottle facilitates the uniform dispersion of moisture, preventing excessive saturation of the bedding. Make sure the bin has sufficient drainage to avoid waterlogging. Raising the bin and positioning a tray beneath it to gather any surplus liquid will effectively control dampness (Palsania *et al.*, 2008).

21.2.6.1.3 Methods of aeration. Rotating or fluffing the bedding material on a regular basis is important for maintaining proper aeration and preventing compression. Enhancing air circulation and avoiding oxygen-deprived circumstances can be achieved by including ventilation holes or employing breathable materials for the bin (Palsania *et al.*, 2008).

21.2.7 Factors influencing vermicompost quality

21.2.7.1 Raw materials

The type of raw materials used in the manufacturing of vermicompost has a substantial impact on its quality. Various source materials contribute diverse nutritional profiles and chemical qualities to the end product.

Research has demonstrated that incorporating raw materials including sheep dung, pomegranate peels, wasted mushroom compost, and different agricultural leftovers into vermicompost increases its nutritious content. A study conducted by A'ali *et al.* (2017) discovered that combining sheep dung and pomegranate peels resulted in elevated amounts of nitrogen, phosphorus, and potassium in the vermicompost product. Further research emphasized that various combinations of kitchen trash, garden waste, and cow dung had a substantial impact on the nitrogen content and overall nutritional composition of the compost. Certain compositions led to greater amounts of nitrogen (Mousavi and Faraji, 2017).

The vermicomposting process of various source materials also modifies physical qualities, including pH and electrical conductivity. By utilizing a blend of cattle manure and horticulture wastes such as straw and biochar, it is possible to enhance the microbial activity and decomposition process, hence yielding superior vermicompost of enhanced quality (Cao *et al.*, 2021).

The selection of ingredients also influences the microbial population present in the vermicompost. Studies have demonstrated that using materials such as cow dung, together with biochar or other organic wastes, can promote a greater variety and more active microbial community. This is important for the efficient cycling of nutrients and improving the overall health of the soil (Chatterjee, Debnath, and Mishra, 2020).

Mixing raw materials like yard trash with additives such as used mushroom compost or cow manure helps organic matter, cellulose, and lignin break down more quickly. As a consequence, the outcome is a vermicompost that is both more abundant in nutrients and more stable (Gong *et al.*, 2019).

The selection of raw materials is crucial in establishing the quality of vermicompost. It is feasible to improve the nutritional profile, microbial activity, and general efficacy of vermicompost as a soil amendment by choosing appropriate blends of organic wastes.

21.2.7.2 Earthworm species

The species of earthworm used in vermicomposting significantly affects the quality of the final product. Different species exhibit varying efficiencies in decomposing organic matter and enriching the compost with nutrients. Table 21.1 shows the list of earthworm species used in vermicomposting.

The quality of vermicompost is significantly influenced by the species of earthworms used in the composting process. Different earthworm species have varying efficiencies in processing organic matter and producing nutrient-rich compost. For example, *E. eugeniae* tends to produce vermicompost with higher nutrient content compared to *E. fetida*. In a study, *E. eugeniae* was found to enhance the nutrient levels significantly, including nitrogen, phosphorus, and potassium, in the vermicompost, making it a superior choice for higher-quality output (Gajbhiye and Satpute, 2014)

TABLE 21.1 List of earthworm species used in vermicomposting process.

Species	Significant features	References
Eisenia fetida	Highly efficient in organic waste decomposition; increases NPK content in vermicompost; tolerates various waste types.	(Garg, Gupta, and Satya, 2006)
Eisenia andrei	Similar to *E. fetida* in efficiency and waste decomposition; often used interchangeably with *E. fetida.*	(Domínguez, 2018)
Eudrilus eugeniae	Known for rapid biomass increase and high reproduction rate; efficient in vermicast production.	(Gajalakshmi, Ramasamy, and Abbasi, 2001)
Perionyx excavatus	Efficient in converting organic wastes into vermicompost; good for mixed waste types.	(Khwairakpam and Bhargava, 2009)
Dendrobaena veneta	Effective in organic waste composting; often compared with other species for its efficiency.	(Suleiman *et al.*, 2017)
Lampito mauritii	Indigenous species known for efficient organic waste processing in tropical conditions.	(Kaviraj and Sharma, 2003)
Drawida willsi	Less efficient compared to other species but still effective in composting aquatic weeds.	(Tabassum-Abbasi *et al.*, 2023)

Furthermore, earthworms not only contribute to the nutrient composition but also influence the microbial community structure within the vermicompost. For instance, *E. fetida* was shown to significantly enhance bacterial and fungal densities, which play crucial roles in the decomposition process and nutrient cycling (Huang *et al.*, 2014). Additionally, Lv *et al.* (2018) observed that earthworms like *E. fetida* had a substantial impact on reducing CH_4 emission but did not have any effect on CO_2 emission. Vermicomposting improved the breakdown of organic matter and the release of nitrogen, while a higher carbon-to-nitrogen ratio lowered greenhouse gas emissions.

Overall, the choice of earthworm species is critical in determining the efficiency of the vermicomposting process and the quality of the final product, with certain species like *E. eugeniae* and *E. fetida* showing notable advantages in enhancing nutrient content and microbial activity.

21.2.7.3 Temperature

Temperature significantly impacts the quality of vermicompost by affecting the biological activities of earthworms and microorganisms. Optimal temperatures, around 25°C, enhance earthworm growth and microbial activity, leading to efficient decomposition and higher nutrient availability. A study by H. Zhang *et al.* (2020) found that vermicompost produced at 25°C had the highest microbial diversity and nutrient content, indicating superior quality.

However, extreme temperatures can be detrimental. High temperatures above 30°C reduce earthworm survival and reproduction, while low temperatures below 15°C slow down metabolic activities, resulting in incomplete decomposition and lower compost quality (Alikhani *et al.*, 2017). Temperature fluctuations also affect the physicochemical properties of vermicompost. Cooler temperatures tend to increase electrical conductivity (EC) and nutrient content, which benefits soil health, but excessive heat can lead to rapid nutrient loss and degrade compost quality (Garg and Gupta, 2011).

Maintaining an optimal temperature range of 20 to 25°C is crucial for producing high-quality vermicompost. This range supports the biological activities of both earthworms and microorganisms, ensuring efficient organic matter decomposition and nutrient stabilization, which are essential for improving soil health and plant growth.

21.2.7.4 Additives

The inclusion of different additives has a substantial effect on the quality of vermicompost by improving the nutritional composition, microbial activity, and earthworm performance. Carbonaceous additions, such as straw, biochar, and nanocarbon, have various effects on the vermicomposting process. Straw typically promotes the growth and reproduction of earthworms, while biochar and nanocarbon enhance the presence and activity of microbial communities and enzymes, leading to an overall improvement in the quality of vermicompost. A study conducted by Cao *et al.* (2021) revealed that the inclusion of these additives can considerably augment the vermicompost quality index (VQI) and promote the growth of crop biomass.

Organic additives, such as cattle manure and spent mushroom substrate (SMS), are essential for increasing the nutrient content and microbial activity of vermicompost. Studies have shown that the combination of garden waste, bovine manure, and SMS (soil moisture sensor) enhances the survival and reproductive capabilities of earthworms, boosts nutrient levels, and speeds up the breakdown of organic material. The utilization of this combination results in the production of superior-grade vermicompost that possesses increased nutritional availability (Gong *et al.*, 2019).

The addition of inorganic additives such as phosphate rock and fishmeal can improve the quality of vermicompost by boosting the availability of nutrients and the biomass of earthworms. The use of these compounds, particularly when paired with phosphate-solubilizing microorganisms, greatly enhances the chemical characteristics of vermicompost. Nevertheless, many inorganic additions have the potential to reduce nitrogen concentration while simultaneously raising phosphorus content, hence impacting the overall nutritional balance (Khosravi and Zarei, 2018).

Biochar significantly enhances the physical and chemical characteristics of vermicompost. It augments the ability of cations to be exchanged, facilitates the breakdown of organic substances, and boosts the activity of microorganisms and enzymes in compost. An experiment conducted by Gong *et al.* (2018) showed that the inclusion of 6% bamboo biochar in vermicompost led to improved quality, with higher nutrient levels and reduced amounts of heavy metals.

The utilization of a diverse range of organic and inorganic additives might collectively enhance the quality of vermicompost through synergistic effects. Research has demonstrated that the utilization of vermicompost supplemented with biochar and other organic substances can enhance the nutrient composition, microbial function, and decrease the movement of toxic metals, resulting in superior compost of enhanced quality. The significance of choosing suitable additives to enhance vermicompost output is emphasized in this strategy (Khan *et al.*, 2019).

21.2.7.5 Microbial inoculants

Microbial inoculants greatly improve the quality of vermicompost by enhancing nutrient content, expediting the breakdown process, and boosting microbial activity. Microbial inoculants have a key advantage in their capacity to augment nutrient content. By introducing nitrogen-fixing and phosphate-solubilizing bacteria, such as *Azospirillum brasilense* and *Rhizobium leguminosarum*, into vermicompost, the levels of nitrogen and phosphorus can be enhanced. Vermicompost is a highly effective organic fertilizer due to its essential nutrients that are vital for plant growth (Rajasekar, Daniel, and Karmegam, 2012).

Furthermore, the introduction of microbial inoculants accelerates the breakdown of organic matter, resulting in the expedited generation of superior vermicompost. For example, the addition of fungi such as *Phanerochete chrysosporium* and *Trichoderma reesei*, as well as bacteria like *Azotobacter chroococcum* and *Bacillus cereus,* to organic wastes greatly improves the breakdown of complex organic compounds. The enhancement enhances the efficacy of the vermicomposting procedure (Kumar and Shweta, 2013).

In addition, certain microbial strains enhance microbial activity in vermicompost, resulting in increased enzyme activities and improved nutrient cycling. Introducing *Bacillus polymyxa,* a bacterium that fixes nitrogen, has been proven to enhance the levels of phosphatase and urease activity in vermicompost. These enzymes play a crucial role in decomposing organic matter and releasing nutrients, hence improving the overall quality of the vermicompost (Pramanik, Ghosh, and Chung, 2010).

Moreover, the utilization of microbial inoculants in conjunction with other fertilizers might further augment the grade of vermicompost. The results of field trials have shown that adding both vermicompost and bio-fertilizers such as *Azospirillum* and *Azotobacter* to the soil has a considerable positive impact on the amount of organic carbon in the soil and the yields of crops. This demonstrates the combined beneficial effects of these inoculants (Shukla *et al.*, 2013).

Microbial inoculants improve the quality of vermicompost by increasing the amount of nutrients, speeding up the decomposition process, enhancing microbial activity, promoting the formation of humus, and forming beneficial interactions with other fertilizers. These enhancements enhance the efficacy of vermicompost as an organic soil additive, fostering superior plant development and soil health.

21.2.7.6 Duration and process

The duration and procedure of vermicomposting have a substantial effect on the quality of the produced vermicompost. Producing high-quality compost requires optimal maturation periods and adequate pre-composting activities. According to a study conducted (Alidadi *et al.*, 2016), a 75-day maturation period for vermicomposting municipal solid waste and carbonaceous materials is ideal for improving quality indicators such as total nitrogen, phosphorus, and lignin levels while also decreasing the carbon-to-nitrogen (C/N) ratio.

Increasing the length of vermicomposting further improves its quality. For example, Jamaludin and Mahmood (2010) showed that increasing the duration of the process from 10 to 30 weeks resulted in higher levels of macronutrients and lower concentrations of heavy metals, leading to an improvement in the quality of vermicompost. Prior to composting, pre-composting activities are also essential. Frederickson, Howell, and Hobson (2007) showed that the combination of thermophilic pre-composting and vermicomposting leads to increased nutrient content and improved fragmentation of organic materials, surpassing the findings obtained by windrow composting.

Efficiently managing the duration and process of vermicomposting, which includes determining the ideal maturation periods and implementing pre-composting activities, is crucial for creating vermicompost of superior quality. This approach results in vermicompost that has increased nutrient content and reduced levels of pollutants.

21.2.7.7 Interaction with other fertilizers

The interaction between vermicompost and other fertilizers significantly enhances soil nutrient availability and plant growth. Combining vermicompost with bio- and mineral fertilizers improves soil properties and crop yields. The integration of vermicompost with nitrogenous and phosphate bio-fertilizers significantly increased available nitrogen and phosphorus in the soil, leading to higher potato yields (Hou *et al.*, 2024). This combination was particularly effective in enhancing the number of tubers and total yield per plant. In another study, the integration of vermicompost with inorganic fertilizers was shown to improve nutrient uptake and enhance plant growth. In field trials with sweet corn, using a mix of vermicompost and inorganic fertilizers resulted in yields similar to or higher than those achieved with conventional inorganic fertilization alone (Lazcano *et al.*, 2011).

21.2.7.8 Soil properties

The usefulness and efficiency of vermicompost as an organic amendment are influenced by several soil parameters, including pH, texture, organic matter content, and microbial activity.

The soil pH has a considerable impact on the efficiency of vermicompost, altering the availability of nutrients, the activity of microorganisms, and the overall effectiveness of the process. Higher pH values in alkaline soils increase the solubility of nutrients from vermicompost, thus making them more accessible for plants (Uz *et al.*, 2016). Vermicompost has the ability to regulate soil pH, enhancing the activity of microorganisms and the functioning of enzymes in soil conditions that are neither acidic nor alkaline (H. Zhang *et al.*, 2020). In acidic soils, vermicompost aids in the immobilization of heavy metals, hence reducing their accessibility (Liu *et al.*, 2019). It also enhances soil fertility by changing pH levels and increasing nutrient availability (Mahmud, Abdullah, and Yaacob, 2018). The physical interactions with vermicompost are influenced by soil texture, which is determined by the amounts of sand, silt, and clay. The inclusion of vermicompost in sandy soils can enhance water retention and nutrient-holding ability because of its substantial organic matter composition. Vermicompost can enhance aeration and decrease compaction in clayey soils, hence promoting improved root growth and microbial activity (Aksakal, Sari, and Angin, 2016).

Soils that have a higher concentration of organic matter create a favorable environment for the breakdown and incorporation of vermicompost. The presence of organic materials in vermicompost sustains microbial communities that facilitate the decomposition and conversion of nutrients. In contrast, in soils with a low amount of organic matter, the microbial community may exhibit reduced activity, hence impeding the decomposition process (Tejada and González, 2009). The microbial activity in soil synergistically interacts with the microbial populations introduced via vermicompost. Dynamic soil microbial populations can accelerate the decomposition of organic substances in vermicompost, resulting in expedited nutrient liberation. Increased microbial activity also facilitates the development of advantageous microbial communities that can enhance the overall quality and productivity of the soil (Arancon, Edwards, and Bierman, 2006).

The physical characteristics of soil, such as its porosity and the stability of its aggregates, affect how vermicompost is distributed and incorporated into the soil. Soils that are well-structured and have strong aggregate stability facilitate the thorough integration and blending of vermicompost, hence improving its efficacy. The presence of poorly organized soils can hinder the flow and even distribution of vermicompost, hence diminishing its advantages (Aksakal, Sari, and Angin, 2016).

Soil with a high cation exchange capacity (CEC) has the ability to retain and exchange a greater amount of nutrients provided by vermicompost. This characteristic enables the soil to retain vital nutrients produced from vermicompost, thus extending their availability to plants for a longer duration. Soils with a poor CEC may necessitate more frequent applications of vermicompost in order to sustain nutrient availability (Uz *et al.*, 2016).

22.3 Benefits of vermicomposting

22.3.1 Environmental benefits

Vermicomposting greatly decreases the amount of organic waste that is disposed of in landfills. Vermicomposting reduces methane emissions, a powerful greenhouse gas generated during anaerobic decomposition in landfills, by diverting organic waste away from them (Lim, Lee, and Wu, 2016). Vermicomposting produces compost that improves soil structure, aeration, and water retention. Additionally, it enhances microbial activity and promotes a wider range of species in the soil, both of which are essential for preserving the health of soil ecosystems (Saha *et al.*, 2012). Vermicompost is abundant in vital nutrients, hence decreasing reliance on synthetic fertilizers. The use of organic fertilizers (e.g., organic manure), either alone or in combination with inorganic fertilizers, can help reduce the environmental impact associated with the production and application of synthetic fertilizers. Additionally, this practice mitigates soil and water pollution caused by fertilizer runoff and enhances agroecosystem resilience against invasive species such as weeds (Ghosh et al., 2020, 2022; Pereira et al., 2014). Vermicomposting aids in carbon sequestration by transforming organic waste into durable organic material that may be stored in the soil. Along with other interventions, vermicomposting aids in the reduction of climate change by extracting carbon dioxide from the atmosphere and storing it in a more secure state (Ghosh *et al.*, 2023; Hossain *et al.*, 2023; Pigatin *et al.*, 2016).

Vermicomposting provides a range of environmental advantages, such as waste minimization, enhancement of soil health, reduced dependence on chemical fertilizers, carbon capture, and less soil erosion. The aforementioned benefits render it a sustainable approach that simultaneously promotes environmental conservation and agricultural productivity.

21.3.2 Soil health and fertility enhancement

Vermicompost enhances soil structure by improving aeration, porosity, bulk density, and water retention capacity. As a result, there is enhanced root penetration and improved plant growth. The enhanced porosity and water-retention capacity play a vital role in sustaining soil moisture and mitigating soil erosion (UZ *et al.*, 2016). Vermicompost enriches the soil by increasing its organic matter content, hence improving the accessibility of vital nutrients such as nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), and magnesium (Mg), as well as micronutrients like zinc (Zn) and iron (Fe). This process of enrichment enhances the absorption of nutrients by plants, resulting in enhanced crop productivity (Sujatha and Bhat, 2012). Vermicompost injection augments soil microbial activity and variety, promoting a robust soil ecosystem. It enhances the proliferation of advantageous microorganisms, such as nitrogen-fixing bacteria and mycorrhizal fungi, which enhance the process of nutrient cycling and the overall health of plants. This enhanced microbial activity also contributes to the suppression of soil-borne illnesses (Maji *et al.*, 2017). Vermicompost is enriched with plant growth hormones and humic acids, which effectively promote plant growth and development. These chemicals enhance root development, optimize nutrient absorption, and bolster resistance against pests and illnesses. Research conducted by Rehman *et al.* (2023) and Joshi, Singh, and Vig (2015) has demonstrated that using vermicompost can enhance crop yields and improve the quality of produce. Consistent use of vermicompost enhances the CEC of the soil, enabling it to effectively retain a greater amount of nutrients and make them accessible to plants for a longer duration. The long-term enhancement of soil fertility contributes to the maintenance of agricultural productivity and the reduction of reliance on chemical fertilizers (Chatterjee, Debnath, and Mishra, 2020).

21.3.3 Nutrient recycling and carbon sequestration

Vermicompost greatly enhances the soil by providing vital nutrients like nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), as well as micronutrients such as zinc (Zn) and iron (Fe). These minerals are easily accessible to plants, enhancing soil fertility and promoting plant development. Vermicompost often has a more abundant nutrient composition compared to regular compost, resulting in improved crop productivity (Lim *et al.*, 2015).

Vermicompost enriches the microbial biodiversity in the soil by adding a diverse range of helpful microorganisms, such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi. These microorganisms have crucial functions in the process of nutrient cycling, as they decompose organic materials and transform nutrients into forms that can be readily taken up by plants. The existence of these microorganisms also aids in inhibiting soil-borne infections and enhancing plant well-being (Pathma and Sakthivel, 2012).

Vermicomposting affects the process of nitrogen cycling by enhancing nitrogen retention and decreasing nitrogen leaching. The presence of beneficial microorganisms in vermicompost facilitates the processes of nitrification and mineralization, hence ensuring a consistent provision of nitrogen to plants. This diminishes the use for artificial nitrogen fertilizers, hence enhancing the sustainability of agricultural methods. The impact of vermicompost on nitrogen dynamics can differ based on the rates of application and the types of vermicompost used (Lv *et al.*, 2020).

Vermicompost treatment can effectively balance soil pH, hence decreasing soil acidity and improving nutrient accessibility. This enhances the overall quality and productivity of the soil, resulting in improved crop production. The nutritional composition of vermicompost contributes to the preservation of soil structure and fertility in the long run (Mahmud, Abdullah, and Yaacob, 2018).

Vermicompost is rich in humic acids, which play a vital role in the process of nutrient cycling and the overall fertility of the soil. Humic acids enhance plant nutrient absorption, improve soil composition, and augment the soil's ability to retain water. These compounds additionally promote the growth of roots and the overall health of plants, thereby supporting the implementation of more sustainable agricultural methods (Martinez-Balmori *et al.*, 2014).

Vermicompost improves soil nutrient levels and contains beneficial chemicals like humic acids and plant hormones that promote plant growth. These chemicals enhance root growth, optimize nutrient uptake, and bolster resistance against pests and diseases. This results in enhanced plant health and increased agricultural productivity (Goswami, Gorai, and Mandal, 2021).

Vermicomposting aids in carbon sequestration by promoting the accumulation of soil organic carbon and the stabilization of carbon in soils through different methods. Here are the primary methods by which vermicomposting contributes to carbon sequestration. Vermicomposting enhances the overall organic carbon content in soils. Research has demonstrated that the use of vermicompost leads to a substantial rise in total organic carbon (TOC) levels, as well as of other stable carbon components including humic and fulvic acids. These compounds play a vital role in the long-term storage of carbon (Sarma *et al.*, 2018). Vermicompost treatment improves soil physical and chemical characteristics, resulting in enhanced soil structure and greater capacity for carbon retention. Research conducted by Ding *et al.* (2021) has demonstrated that the combination of deep tillage and vermicompost application leads to a substantial enhancement in soil quality and a greater capacity for carbon sequestration, surpassing the effects of other supplements. Vermicomposting is the process of transforming organic waste into stable organic matter using earthworms and microbes. This process decreases the carbon/nitrogen ratio and enhances the stability of organic matter, hence reducing its susceptibility to decomposition and the release of CO_2 (Aira and Domínguez, 2008).

Vermicomposting has the potential to decrease greenhouse gas emissions in comparison to conventional composting techniques. A study conducted by Nigussie *et al.* (2016) discovered that it can effectively reduce the release of nitrous oxide and methane, thereby leading to a decrease in the overall carbon footprint associated with waste management. Vermicomposting greatly decreases methane emissions in comparison to thermophilic composting. Earthworms improve the oxygen-rich conditions in the compost, reducing the oxygen-deprived conditions that usually lead to the production of methane (Nigussie *et al.*, 2016). Research has demonstrated that vermicomposting can lead to a significant decrease in methane emissions, with reductions ranging from 22 to 26%. While earthworm activity may lead to a minor rise in carbon dioxide emissions as a result of increased microbial respiration, the overall effect on greenhouse gas (GHG) emissions is favorable due to substantial decreases in methane and nitrous oxide, which have significantly higher global warming potential (Poblete, Cortes, and Munizaga-Plaza, 2022). Vermicomposting limits the release of ammonia into the air and enhances the preservation of nutrients like nitrogen in a stable state. This reduces the reliance on synthetic fertilizers, which are a source of greenhouse gas emissions during their production and application (Raza *et al.*, 2021). The sequential procedure of pre-composting followed by vermicomposting improves the stability of organic wastes, resulting in reduced emissions of noxious gases. Research indicates that employing this integrated method can result in a reduction of methane emissions by 10 to 35% and nitrous oxide emissions by 23 to 40% (Wang *et al.*, 2014).

21.4 Risks associated with vermicomposting

21.4.1 Contamination risks

The presence of heavy metals, pesticides, and other harmful compounds in the final compost product is a major concern in vermicomposting due to chemical contamination. These pollutants (heavy metals) can have a negative impact on the well-being of crops, the quality of soil, and the health of humans by being transferred through the food chain (Chowardhara *et al.*, 2024; Hossain *et al.*, 2023; Majumdar *et al.*, 2024).

Heavy metals, including cadmium (Cd), copper (Cu), zinc (Zn), and lead (Pb), have the ability to remain present in vermicompost throughout time. While earthworms have the ability to absorb certain metals, this process does not entirely prevent the possibility of these contaminants persisting in the compost, which might potentially be harmful to plants and soil health (Bhat *et al.*, 2018). The presence of both heavy metals and antibiotics in vermicompost might result in the excessive activation of resistance genes, which can then be transmitted to soil microbes, hence exacerbating the risk of contamination (Liu *et al.*, 2019). Although heavy metals may become initially immobilized in the vermicompost,

alterations in soil conditions might cause these pollutants to be released anew, rendering them accessible and potentially endangering plants and soil organisms. Sun *et al.* (2020) observed earthworms primarily absorb metals such as Zn and Cu, and these metals can be returned to the soil if the earthworms die and degrade.

Vermicompost produced from materials polluted with pesticides can contain residues that can be harmful to soil microbial communities and the health of plants. The presence of these residues can hinder the microbial activity in the vermicompost, hence impacting the compost's overall quality and safety (Fernández-Gómez *et al.*, 2011). The inclusion of hazardous organic compounds in the waste materials utilized for vermicomposting can result in the buildup of these toxins in the end compost product. Phytotoxicity can occur, leading to adverse effects on seed germination and plant growth (Sanchez-Hernandez and Domínguez, 2017). The presence of excessive salt levels (>0.2%) in kitchen wastes might have detrimental effects on both the growth of earthworms and the quality of the compost produced through vermicomposting. Elevated salinity inhibits the optimal development of earthworms and diminishes the effectiveness of the composting procedure, resulting in inferior vermicompost quality that may have adverse impacts on plants (Wu *et al.*, 2019).

Vermicomposting, a method of composting, can reduce pathogens through direct mechanisms like microbial inhibition and coelomic fluid secretion, as well as indirect ones like competition and aeration. It also contributes to pathogen reduction through native microbe stimulation and aeration through burrowing activity. However, the effectiveness of vermicomposting depends on the species of earthworm and the type of pathogen, specifically Gram-positive or -negative, due to differences in cell wall composition (Swati and Hait, 2018).

The presence of heavy metals, pesticides, hazardous organic compounds, and pathogens in vermicomposting poses a major risk of chemical contamination. Effective oversight and consistent supervision of the composting procedure are crucial in order to minimize these hazards and guarantee the security and effectiveness of the end compost product.

21.4.2 Odor issues

Odor problems in vermicomposting can occur due to factors such as the nature of the waste utilized, the process of decomposition, and the microbiological activities involved. The presence of these scents can create difficulties for both small-scale and large-scale vermicomposting operations.

Odor emissions frequently occur when organic material decomposes in vermicomposting. Food waste decomposition can result in the emission of ammonia (NH_3) and volatile amines ($R\text{-}NH_2$), which can produce unpleasant odors (Kim *et al.*, 2019). Volatile organic molecules, such as amines and sulfur compounds, are major contributors to the stench in vermicomposting. These chemicals are generated through the microbial decomposition of organic waste and can result in potent and frequently unpleasant smells (Andraskar, Yadav, and Kapley, 2021). Hydrogen sulfide is a gas that can be released during the vermicomposting process, especially when handling waste materials that are rich in protein. H_2S emits a distinct odor resembling that of rotten eggs and can be discharged in substantial amounts if the composting process is not adequately controlled (Li *et al.*, 2020). The choice of organic waste utilized in vermicomposting might have a substantial impact on the olfactory characteristics. Wastes that have a high moisture content and protein levels, including kitchen waste and manure, tend to create stronger and more unpleasant smells because they break down quickly with the help of microorganisms and release volatile compounds (Garg and Gupta, 2009). Odor production in vermicomposting is substantially influenced by factors such as pH, temperature, and aeration. Inadequate aeration can result in anaerobic conditions, which are more prone to generating malodorous gases such as hydrogen sulfide and ammonia. By maintaining ideal environmental conditions, it is possible to reduce or alleviate these odor concerns (Andraskar, Yadav, and Kapley, 2021).

21.4.3 Pathogen presence and health concerns

Vermicomposting is an environmentally friendly approach to managing organic waste, although it encounters notable constraints concerning the existence and mitigation of pathogens. Vermicomposting lacks a thermophilic stage, which is crucial for eliminating pathogens in traditional composting. Consequently, specific disease-causing microorganisms may endure the vermicomposting procedure, presenting potential hazards to human health (Hénault-Ethier, Martin, and Gélinas, 2016). Due to variations in cell wall composition, the efficacy of vermicomposting is contingent on the earthworm species and the pathogen type, specifically Gram-positive or negative (Swati and Hait, 2018). Research has indicated that vermicomposting can effectively decrease the presence of pathogens like *E. coli* and *Salmonella*. However, it may not be equally efficient against all types of pathogens. For example, microorganisms such as *Clostridium* and certain coliforms can be present in the end product of vermicompost (Aira *et al.*, 2011). The efficacy of pathogen reduction in vermicomposting may vary based on the specific pathogen and the earthworm species employed. The effectiveness of reducing pathogens varies depending on the varied impacts of earthworm digestion and microbial interactions (Roubalová *et al.*,

2020). Occasionally, vermicompost products may surpass the permissible thresholds of bacterial pathogens, resulting in a failure to comply with legal sanitation regulations. The irregularity can be ascribed to fluctuations in the raw materials used, the surrounding conditions, and the management of the manufacturing process (Soobhany, 2018).

21.5 Challenges in vermicomposting

21.5.1 Scalability and operational challenges

Vermicomposting, while an efficient and environmentally beneficial waste management process, encounters many obstacles in terms of scalability and operational issues, which might hinder its broad implementation and effectiveness. An important obstacle is the maintenance of ideal temperature and moisture conditions, which are essential for the life and functioning of earthworms. For vermicomposting to be efficient, it is necessary to maintain particular temperature ranges between 15 and 25°C and moisture levels around 60 to 70%. Managing these characteristics in extensive operations may pose challenges and incur significant expenses, particularly under fluctuating climate circumstances. This may have a substantial influence on the efficiency and sustainability of the process (Solanki and Mahore, 2021). In addition, Solanki and Mahore (2021) pointed out that the establishment of a large-scale vermicomposting operation requires a significant upfront investment in infrastructure, including beds, shelters, and systems for controlling temperature and moisture. The continuous expenses associated with maintenance and operation might be substantial, thereby discouraging small-scale farmers or enterprises from embracing this technology.

The vermicomposting process may be considerably influenced by the quality and consistency of the organic waste utilized as feedstock. Irregular feedstock might result in unequal rates of decomposition and varying quality of compost. Large-scale operations have a significant problem in managing a wide range of organic waste streams in order to achieve consistency. Another notable constraint is that vermicomposting lacks a thermophilic step, which is crucial for eliminating pathogens in traditional composting. This might result in the long-term presence of detrimental microbes in the end compost product, which can pose health hazards. To guarantee the absence of pathogens in vermicompost, it is necessary to apply extra treatments and closely monitor the process. However, these measures increase the complexity and expense of the process (Hénault-Ethier, Martin, and Gélinas, 2016).

The spatial demands of vermicomposting may pose a notable constraint, especially for extensive operations and in urban settings where space is scarce. Vermicomposting needs a considerable amount of room to accommodate the earthworm beds and efficiently handle organic waste. Proper aeration and temperature management are crucial for the health and activity of the earthworms; thus, it is important to ensure that each bed is sufficiently separated. The limited availability of land in densely populated places is a challenge for implementing vermicomposting, which is essential for urban animal husbandry and organic waste management. Research done in Kampala, Uganda, emphasized the geographical constraints linked to vermicomposting systems. The study highlighted the need of having enough room to establish vermicomposting units, particularly in metropolitan areas where land is limited and costly (Komakech *et al.*, 2016).

Vermicomposting requires significant labor and upkeep. Regular monitoring and maintenance are necessary to guarantee the earthworms are in ideal circumstances. Tasks include the activities of providing nourishment, infusing with air, and sustaining optimal levels of moisture. Large-scale operations incur significant personnel costs and logistical complications, which may pose obstacles for some operators (Sherman, 2002).

Ultimately, the technology used in vermicomposting systems, including reactors and continuous flow systems, may not readily adapt to larger-scale operations. The scalability and efficacy of these systems may be influenced by variations in earthworm behavior, rates of waste mineralization, and environmental variables (Suthar, 2010).

Vermicomposting encounters notable difficulties in terms of scalability and operations. These issues include the need for meticulous environmental management, consistent quality of feedstock, efficient elimination of pathogens, and major investments in infrastructure and personnel. It is essential to tackle these problems in order to achieve universal acceptance and effectiveness of vermicomposting as a sustainable approach to managing trash.

21.5.2 Regulatory compliance and standards

The regulatory requirements and standards for vermicomposting differ based on the nation and location, but they often come under the scope of wider environmental protection regulations that oversee waste management, soil health, and water quality. In the United States, the USDA National Organic Program (NOP) offers rules for the use of compost and vermicompost in organic farming. These criteria ensure that the compost adheres to organic requirements (USDA, Organic

Crop Production). In addition, the Organic Materials Review Institute (OMRI) provides comprehensive criteria for compost quality, guaranteeing that products adhere to organic certification requirements (OMRI, Compost Standard).

The EU Regulation 2019/1009, also known as the Fertilising Products Regulation, establishes stringent guidelines for fertilizers, including compost. These guidelines include several aspects such as safety, quality, and labeling regulations. In addition, there are typically unique national guidelines that support and enhance these broad standards. For instance, some nations within the European Union may impose stricter criteria for the production and use of compost.

India's regulatory framework encompasses the Municipal Solid Waste (Management and Handling) Rules, 2016, which advocate for the implementation of composting and vermicomposting as integral components of solid waste management systems. The Fertilizer (Control) Order, 1985, establishes criteria for compost quality, which includes restrictions on heavy metals and other impurities. The National Skills Qualification Framework (NSQF) defines the necessary skills for vermicompost producers, guaranteeing compliance with quality and safety criteria throughout the manufacturing process.

Important areas of compliance for vermicomposting operations are acquiring permits and licenses to guarantee compliance with local environmental and health requirements. Operational requirements are crucial and include the careful selection of sites to avoid the pollution of water sources, the management of odors to reduce inconvenience to adjacent inhabitants, and the control of pests like flies and rats. In addition, facilities must adhere to product quality standards, which include the eradication of pathogens, restrictions on contaminants, and fulfillment of nutrient content criteria. These measures are essential to guarantee the effectiveness of compost as a soil supplement. Consistent surveillance and submission of reports to regulatory authorities ensure adherence to these criteria.

Health and safety standards guarantee the provision of secure working environments for workers, which includes the use of protective equipment and instruction in managing organic waste and compost products Hambach et al. (2012). Optimal methods in vermicomposting involve separating the sources of waste to minimize impurities and enhance the quality of the compost. It is also important to conduct public awareness campaigns to educate the community about the advantages and techniques of vermicomposting. Additionally, investing in research and development is crucial to improve the processes and quality of the final product (OMRI, Compost Standard).

By strictly following these regulatory compliances and requirements, vermicomposting plants may function in a way that is environmentally sustainable and create compost products of exceptional quality, which in turn enhance environmental health and agricultural production.

21.5.3 Variability in vermicompost quality

The quality of vermicompost may vary according to several variables, such as the kinds of raw materials used, the specific earthworm species involved, and environmental circumstances like temperature and moisture. Various organic feedstocks, including kitchen trash, agricultural wastes, and manure, provide unique nutritional profiles and chemical properties to the resulting compost. For example, vermicompost produced from bovine dung generally has a greater nutritional composition in comparison to that formed from garden waste (Cao *et al.*, 2021). The fluctuation in the nutritional composition of the input materials has a substantial impact on the overall excellence of the vermicompost generated.

The choice of earthworm species used in the vermicomposting process is also a critical factor in determining the compost's quality. Various kinds of earthworms demonstrate different levels of effectiveness in decomposing organic materials and enhancing the compost with nutrients. *E. eugeniae* is recognized for its capacity to generate vermicompost with elevated nutrient concentrations in comparison to *E. fetida,* a species that is extensively used due to its adaptability and effectiveness (Garg, Gupta, and Satya, 2006). The selection of earthworm species may result in notable variations in the nutritional composition and microbial function of the vermicompost.

The quality of vermicompost is significantly influenced by environmental variables, particularly temperature and moisture levels. The successful activity of both earthworms and microorganisms engaged in the decomposition process requires optimal temperature ranges (15−25°C) and moisture levels (70−90%) (H. Zhang *et al.*, 2020). Deviation from these optimum circumstances might result in decreased earthworm activity, diminished decomposition rates, and reduced nutrient availability in the end product. In addition, the use of additives like biochar and microbial inoculants might augment the vermicompost's quality by enhancing nutritional composition and microbial variety (Cao *et al.*, 2021).

The length of time it takes for vermicomposting to occur and the techniques used to control the composting conditions also have a role in the variation in compost quality. Extended composting durations often lead to the production of vermicompost, which is more stable and has a higher concentration of nutrients. This is because the longer period allows for complete breakdown and transformation of nutrients (Alidadi *et al.*, 2016). Implementing pre-composting treatments and maintaining regular monitoring of environmental variables may enhance the composting process and minimize variations in the end result.

Contamination hazards related to heavy metals, pesticides, and other dangerous compounds might contribute to the variability in the quality of vermicompost. The presence of these pollutants and emerging pollutants like microplastics in the compost may endure and provide hazards to the health of plants and soil when the compost is used (Cui *et al.*, 2022; Garai *et al.*, 2024; Bhat *et al.*, 2018). To avoid these hazards and assure high-quality vermicompost, it is essential to use effective management techniques, such as meticulous raw material selection and frequent contaminant testing.

Ultimately, the quality of vermicompost is influenced by several variables such as the specific raw materials used, the earthworm species involved, the prevailing environmental conditions, and the potential presence of pollutants. Comprehending and controlling these aspects is essential for creating top-notch vermicompost that satisfies the requirements of sustainable agriculture and enhances soil health.

21.6 Economic considerations

21.6.1 Market potential

The market potential for vermicomposting is substantial, driven by the expanding organic farming sector, increasing adoption of sustainable agricultural practices, and the need for effective waste management solutions (Kavitha, 2023). As consumers demand more organic products, farmers are shifting toward organic fertilizers like vermicompost to meet market demands and enhance soil health (Arumugam *et al.*, 2013). Vermicomposting is also becoming integral to urban and home gardening, where it offers a sustainable way to recycle organic waste and enrich soil quality. Technological advancements have made vermicomposting more efficient and scalable, further boosting its market potential (Dey Chowdhury *et al.*, 2023). Additionally, government policies and incentives promoting organic farming and sustainable waste management are accelerating the adoption of vermicomposting. This coupled with growing environmental awareness and the push toward a circular economy positions vermicomposting as a key player in the future of sustainable agriculture and waste reduction (Samal *et al.*, 2019). Despite challenges like initial setup costs and the need for expertise, the overall outlook for vermicomposting is promising, with significant opportunities for growth across various sectors (Hussaini, 2013). According to the market report, the Global Vermicompost Market size is estimated to be worth USD $87,680 million in 2023 and is projected to reach USD $234,369.43 million by 2030, growing at a CAGR (Compound Annual Growth Rate) of 15.19% from 2023 to 2030.

21.6.2 Cost-benefit analysis

The cost-benefit analysis of vermicomposting reveals a favorable outlook in terms of market demand. Initial costs involve setting up compost bins, purchasing worms, and maintaining optimal conditions, alongside ongoing operational expenses such as feeding, maintaining the system, and labor (Hussaini, 2013). However, these costs are outweighed by the significant benefits. Vermicompost, a high-quality organic fertilizer rich in nutrients, commands a premium price in the expanding organic farming sector, urban gardening, and professional landscaping markets. Additionally, vermicomposting reduces waste disposal costs and lowers the need for chemical fertilizers, resulting in substantial savings (Gao *et al.*, 2015). The environmental benefits, such as promoting sustainability and improving soil health, further enhance its appeal. With growing demand from various sectors, including organic agriculture, urban home gardening, and institutional adoption, the economic and environmental advantages of vermicomposting present a compelling case for its adoption, indicating robust market potential and profitability (Krajcso, 2018).

Gross margin is defined as the difference between the gross return and the variable costs incurred by Dillon and Hardaker (1993). The gross margin was computed using the following formula:

- Gross margin (Rs.) = Gross return in Rs. − Total variable cost in Rs.
- Where Gross return = Price in Rs. × Total quantity produced in kg
- Total variable cost = Summation of cost incurred in all the variable items

Similarly, net profit was calculated as:

- Net profit = Gross return − Gross cost
- Where Gross cost (Rs.) = Total fixed cost (Rs.) + Total variable cost (Rs.)
- The benefit-cost analysis was carried out by using following formulas:
  - Benefit-cost ratio (B: C1) = Gross return (Rs.)/Total variable cost (Rs.)
  - Benefit-cost ratio (B: C2) = Gross return (Rs.)/Gross cost (Rs.)
  - Net Benefit (NB) = Total Benefits (TB) − Total Costs (TC)

21.6.3 Financial viability and economic sustainability

The financial viability and economic sustainability of vermicomposting have been extensively studied in recent research papers. Vermicomposting, a cost-effective and eco-friendly technology, has shown promising results in converting organic wastes into value-added (Dey Chowdhury *et al.*, 2023). Studies have highlighted that vermicompost can significantly reduce the cost of food production, increase crop yields, and decrease water demand, leading to higher profits for farmers (Thirunavukkarasu *et al.*, 2022). Additionally, the use of earthworms as a protein supplement further enhances the economic perspectives of vermicomposting (Kavitha, 2023). Research has also emphasized the potential of vermicomposting in soil fertility enhancement, waste management, and bioremediation, making it a sustainable solution for organic waste treatment (Zheng *et al.*, 2024). The combination of high market demand, cost savings, and positive environmental impacts ensures that vermicomposting is not only financially viable but also a sustainable economic practice.

21.7 Strategies for mitigating risks and overcoming challenges

21.7.1 Best practices in vermicomposting

Vermicomposting is a very efficient technique for handling organic waste and generating compost of exceptional quality. In order to optimize the advantages and effectiveness of vermicomposting, it is essential to adhere to a number of recommended procedures.

Waste sorting and preprocessing are crucial to guarantee that only biodegradable materials are used in vermicomposting. To avoid contamination, it is necessary to eliminate nonbiodegradable materials such as plastics and metals. Preprocessing, which involves shredding and adjusting moisture levels, enhances the pace of decomposition and increases the effectiveness of the procedure.

The efficacy of vermicomposting is heavily contingent on the maintenance of appropriate environmental conditions for the earthworms. The optimal temperature range is 15 to 25°C, while the recommended moisture level should be maintained at around 60 to 70%. Optimal aeration and pH values ranging from 6.4 to 7.6 are essential for maintaining the well-being and functionality of the earthworms (H. Zhang *et al.*, 2020).

It is crucial to guarantee the quality and uniformity of the feedstock. For organic waste to be effective, it must have a well-proportioned combination of carbon-rich (browns) and nitrogen-rich (greens) materials. This ensures that the earthworms get the essential nutrients and maintain an ideal carbon-to-nitrogen (C/N) ratio. Irregular feedstock may result in uneven breakdown and reduced compost quality (Blouin *et al.*, 2019).

Consistent monitoring and maintenance are essential for the prosperity of vermicomposting. This entails monitoring the moisture levels, temperature, and pH of the composting material, as well as assessing the well-being and vitality of the earthworms. Consistently providing food and regularly rotating the compost aids in keeping it well aerated and prevents the development of anaerobic pockets. These pockets may lead to unpleasant smells and hinder the decomposition process (Pirsaheb, Khosravi, and Sharafi, 2013).

Stocking density refers to the number of animals that are kept in a certain area or volume of space. It is an important factor to consider in animal husbandry since it may affect the health and well-being of the animals. Feeding rate, on the other hand, refers to the amount of food that is provided. It is crucial to determine the ideal stocking density and feeding rate in order to maximize the efficacy of vermicomposting. According to research conducted by Ndegwa, Thompson, and Das (2000), the most effective combination for converting substrate into earthworm biomass and high-quality vermicompost was a stocking density of 1.60 kg worms/m^2 and a feeding rate of 0.75 kg feed/kg worms/day.

The integration of vermicomposting with classical thermophilic composting may synergistically increase the entire composting process and elevate the quality of the resulting compost. Prior to vermicomposting, pre-composting organic waste via a thermophilic stage may effectively decrease pathogen levels and expedite the decomposition process. The integration of these methods may result in a compost product that is more consistent and uniform in its composition and stability (Ndegwa and Thompson, 2001).

It is crucial to conduct tests on the final vermicompost product to determine its nutritional content, pH level, and moisture level and to check for the presence of pathogens or heavy metals. These tests are necessary to guarantee the quality and safety of the vermicompost for agricultural application. Regular testing is essential for upholding standards and obtaining important input to make any adjustments to the composting process (Sierra *et al.*, 2013).

Adhering to these recommended methods may enhance the efficiency of the vermicomposting process, resulting in the production of top-notch compost and effective management of organic waste. For successful vermicomposting, it is crucial to follow a series of important steps. These include properly separating and preparing waste, maintaining ideal environmental conditions, ensuring the quality of the materials used, regularly monitoring and maintaining the process,

maintaining an optimal density of worms and feeding rate, integrating with traditional composting methods, and regularly testing the quality of the final product.

21.7.2 Technological innovations and advances

Vermicomposting has had substantial technical breakthroughs to overcome its limits and improve its efficiency. These developments prioritize the optimization of environmental conditions, enhancement of pathogen reduction, augmentation of operational efficiency, and integration of new technology.

One significant progress is the innovation of modified vermireactors and continuous-feeding systems. Conventional vermireactors often encounter constraints regarding their spatial capacity and effectiveness. Vermireactors that have been modified by replacing thick vermibeds with damp cloth enable the digestion of greater amounts of organic waste and result in increased production of vermicast (Jain, Singh, and Gupta, 2003). Continuous-feeding vermireactors allow for the continuous input of new waste, which enhances scalability and operating efficiency. However, there are still issues in achieving constant decrease of pathogens (Aira *et al.*, 2011).

The integration of vermicomposting with conventional thermophilic composting has shown efficacy in boosting the entire process. Prior to vermicomposting, pre-composting organic waste via a thermophilic stage may decrease pathogen levels and expedite decomposition, leading to a compost product that is more stable and uniform (Ndegwa and Thompson, 2001).

Recent advancements in automated monitoring and control systems have enabled the effective maintenance of ideal environmental conditions. These systems have the capability to continuously monitor factors such as temperature, moisture, and pH and automatically make adjustments to maintain the most favorable circumstances for earthworms. By using this method, it is possible to decrease the expenses related to labor and enhance the uniformity and excellence of vermicompost (Pagaria, 2014).

Artificial neural networks (ANN) and machine learning models have shown potential in enhancing nutrient recovery in vermicomposting. These models have the capability to forecast nutrient recovery under various situations, enabling enhanced process optimization and increased efficiency. The study conducted by Hosseinzadeh *et al.* (2020) has shown that ANN models outperform standard regression models in accurately predicting total nitrogen and phosphorus recovery.

Researchers have investigated the use of bioinoculants and microbial improvements to boost the effectiveness of vermicomposting. Enhancing nutrient availability and reducing pathogens may be achieved by inoculating vermicompost with beneficial bacteria. Research has shown that the use of enriched vermicompost may greatly enhance the productivity and quality of crops by promoting the process of biological nitrogen fixation and phosphorus solubilization (Padmavathiamma, Li, and Kumari, 2008).

Advanced techniques for separating earthworms have been developed to enhance operating efficiency. Centrifugal force-based novel separators have successfully achieved high separation rates, thereby minimizing the labor-intensive task of manual separation. These separators improve the effectiveness of vermicomposting operations on a wide scale (Lin *et al.*, 2021).

Current study highlights the incorporation of vermicomposting within the circular bioeconomy. This entails using earthworms as a protein source and investigating their capacity to generate useful industrial raw materials. Vermicomposting aids in sustainable waste management by transforming organic waste into compost that is abundant in nutrients, while simultaneously decreasing emissions of greenhouse gases (Dey Chowdhury *et al.*, 2023).

The limitations of vermicomposting have been greatly reduced by technological advancements, including modified and continuous-feeding vermireactors, integration with traditional composting, automated monitoring systems, artificial neural networks, microbial enhancements, and improved earthworm separation technologies. These advancements improve the effectiveness, expandability, and excellence of vermicompost, rendering it a more feasible and enduring choice for the administration of organic waste.

21.7.3 Policy recommendations and supportive initiatives

Vermicomposting, an environmentally friendly method for managing organic waste and improving soil health, would greatly benefit from specific policy proposals and supporting actions. Implementing these methods may optimize the efficacy of vermicomposting, by mitigating its constraints and facilitating its extensive implementation.

Establishing comprehensive standards is essential to guarantee uniformity and safety in vermicomposting activities. Well-defined protocols and benchmarks for vermicomposting operations, including approved feedstock varieties, processing techniques, and quality requirements for the end product, are necessary. In order to ensure the safety of

vermicompost, it is necessary to establish strict laws that regulate the presence of pathogens and heavy metals. These regulations should include frequent testing and certification procedures to maintain high standards and guarantee the safety of the product (Dey Chowdhury *et al.*, 2023).

Monetary incentives and assistance are crucial in promoting the use of vermicomposting. Offering subsidies, grants, and low-interest loans may assist in compensating for the initial charges of establishing vermicomposting systems and the continuous costs of operation, therefore making it financially feasible for farms and companies. Incentivizing the use of vermicomposting systems, particularly for companies dealing with substantial amounts of organic waste, might be made more financially appealing by providing tax exemptions and credits (Rastegari *et al.*, 2023).

Education programs and technical support are crucial for increasing awareness and imparting practical information about vermicomposting. Implementing and advocating for educational initiatives may enhance the comprehension of vermicomposting advantages among farmers, waste management, and the general public. Training seminars provide practical experience in establishing and managing vermicomposting systems. In addition, offering technical support to both new and established vermicomposting businesses guarantees the implementation of optimal methods and adherence to regulatory standards.

Ensuring the growth potential of vermicomposting relies heavily on the development of supporting infrastructure. Investing in the construction of vermireactors and composting units may enable the implementation of large-scale activities. Collaborations between the government and private sector may have a substantial impact on the establishment of these facilities. In addition, the establishment of effective waste collecting and transportation networks may guarantee a consistent supply of organic material for vermicomposting operations. This can be achieved by collaborating with municipal waste management systems to optimize the whole process (Fernández-Gómez *et al.*, 2011). Allocation of funds for research and development is crucial for the progress of vermicomposting technologies and methodologies. Investing in research may enhance the efficiency and scalability of vermicomposting systems. Research might also investigate novel uses for vermicompost and its advantages for various crops and soil compositions. By providing assistance to pilot projects that experiment with cutting-edge vermicomposting technologies and methods, we may establish prototypes that can be replicated on a wider scale (Blouin *et al.*, 2019).

Market development activities are crucial for the promotion of vermicompost use in the fields of agriculture and horticulture. Promoting marketing efforts and conducting demonstrations showcasing the advantages of vermicompost may effectively cultivate customer confidence and stimulate demand. Establishing certification and labeling systems for vermicompost products guarantees their quality and facilitates the distinction between superior vermicompost and inferior alternatives, hence enhancing customer trust (Mahmud, Abdullah, and Yaacob, 2020).

21.8 Future directions and opportunities

21.8.1 Emerging trends in vermicomposting

Vermicomposting is gaining popularity as a sustainable and environmentally friendly way of organic waste treatment. Recent developments in technology have greatly enhanced its efficiency, economic feasibility, and environmental advantages. An important development is the exploitation of many types of earthworms. Studies show that species like *E. fetida* and *E. eugeniae* have diverse levels of effectiveness when it comes to decomposing various organic compounds. Research has shown that the combination of these species may increase the amount of vermicast obtained and boost the nutritional composition in the compost (Katiyar *et al.*, 2023).

Another new strategy includes the use of sophisticated waste mixes. Combining various organic wastes, such as horse manure, mushroom compost, and agro-residues, has been discovered to enhance the nutritional composition and overall quality of vermicompost. An example is a combination of 50% horse manure and mushroom compost, which resulted in the production of vermicompost of superior quality, including increased amounts of organic carbon and nutrients (Abd Elaziz, 2023). This strategy utilizes the distinctive characteristics of different organic elements to produce a better compost product.

Vermifiltration systems are becoming recognized as a novel approach for treating farm dairy wastewater. The practice of using earthworms to filter and breakdown wastewater leads to a considerable reduction in chemical oxygen demand (COD), biological oxygen demand (BOD), and total suspended solids (TSS) present in the wastewater. Vermifiltration offers a sustainable solution for managing wastewater in agriculture, effectively satisfying the requirements for waste treatment and soil improvement (Permana, Sudirja, and Jupesta, 2023).

Another promising strategy is the enrichment of vermicompost with beneficial microbial inoculants. This approach improves the nutritional value and effectiveness of vermicompost as a biofertilizer. Microbial inoculants enhance the

concentrations of nitrogen, phosphate, potassium, and beneficial microorganisms, hence enhancing the overall quality of the compost (Bhargava, Sharma, and Trivedi, 2023). This approach enhances the efficacy of vermicomposting in stimulating plant growth and improving soil health.

The use of Internet of Things (IoT) technology in vermicomposting operations has resulted in the creation of automated systems. These systems continuously monitor and regulate variables such as temperature, moisture, and pH in real time, guaranteeing ideal conditions for composting and minimizing the need for human effort. IoT-enabled vermicomposting containers provide a contemporary and effective method for easy composting (Sahoo *et al.*, 2023).

Emerging toilet systems that use vermicomposting to handle human waste are currently under development. These technologies not only effectively manage garbage but also generate useful compost and minimize the environmental consequences of conventional sanitation procedures. Vermicomposting toilets provide a sustainable method for managing human waste, which is in line with wider environmental objectives (Alonso-Marroquin *et al.*, 2023).

Current advancements in vermicomposting aim to improve the efficiency of waste combinations, use various types of earthworms, include cutting-edge technology such as the IoT, and enhance the quality of compost by introducing microbial inoculation. These advancements are enhancing the efficiency, economic viability, and environmental benefits of vermicomposting, hence encouraging its use in sustainable agriculture and waste management.

21.8.2 Research needs and knowledge gaps

Vermicomposting has garnered considerable interest as an environmentally benign and sustainable approach to managing organic waste. Nevertheless, there are still several study requirements and areas of knowledge that need to be addressed in order to enhance its efficiency and expand its use.

A significant knowledge deficiency exists in the limited comprehension of the mechanics behind the vermicomposting process. This encompasses the interactions between earthworms and microbes that facilitate the breakdown and preservation of organic materials. Comprehending these processes may aid in optimizing conditions and improving the efficiency of the process (Vuković *et al.*, 2021). Investigation is required to ascertain the most favorable parameters for vermicomposting, including temperature, moisture, pH, and aeration. These conditions have a substantial effect on the activity of earthworms and microorganisms, which in turn affects the quality and stability of the vermicompost product. Further research is necessary to develop uniform procedures for various categories of organic waste (Thirunavukkarasu *et al.*, 2022).

Although vermicomposting has shown effectiveness in lowering certain diseases and pollutants, more research is required to fully understand its utility in different situations. The primary objective of research should be to ascertain the degree to which vermicomposting may effectively mitigate pathogens, heavy metals, and many other pollutants present in diverse waste materials. This will aid in the formulation of tactics to guarantee the safety and excellence of vermicompost (Blomström *et al.*, 2016). The understanding of the makeup and function of microbial communities involved in the vermicomposting process remains incomplete. In-depth investigations on the microbial dynamics inside vermicomposting systems may provide insights into the specific roles that various microorganisms play in the degradation process and their impact on the quality of the vermicompost. This information may be used to improve microbial activity by introducing beneficial bacteria via inoculation (Das, Goswami, and Bhattacharya, 2020).

Research is required to optimize the composition of substrate mixes used in vermicomposting. The nutritional contents and physical qualities of various organic wastes have distinct impacts on the vermicomposting process. Research should prioritize the identification of optimal combinations of substrates in order to improve the recovery of nutrients and enhance the quality of compost (Ramnarain, Ansari, and Ori, 2019).

Expanding vermicomposting operations poses technical and economic difficulties. Research is required to provide cost-efficient technologies and techniques for vermicomposting on a big scale. This includes the development of proficient vermireactors, automated surveillance systems, and efficient earthworm separation technologies (Suthar and Singh, 2008).

Further investigation is required to explore the economic aspects of vermicomposting, including conducting a cost-benefit analysis, assessing market potential, and studying customer behavior. An in-depth comprehension of these aspects may facilitate the formulation of feasible business models and facilitate the acceptance of vermicomposting technology among farmers and waste management (Tiwari, Stephen, and Kumar, 2023). Further field-level investigations are necessary to confirm laboratory results and evaluate the practical ramifications of vermicomposting technology in real-life situations. The aforementioned research may provide valuable insights into the operational difficulties, ecological consequences, and efficacy of vermicomposting in various circumstances (Mupambwa and Mnkeni, 2018).

21.9 Conclusion

The role of earthworms, specifically species such as *E. fetida*, is vital in the process of decomposing organic materials, resulting in the creation of nutrient-dense vermicast. For vermicomposting to be effective, it is crucial to maintain optimal environmental conditions, including a temperature range of 15 to 25°C and moisture levels of 70 to 90%. By including carbonaceous and organic materials, together with microbial inoculants, the quality of vermicompost is improved by the augmentation of nutritional content and microbial activity. Vermicomposting greatly raises soil nitrogen levels and promotes microbial biodiversity, hence improving plant growth and soil health via nutrient recycling. Environmental advantages: Vermicomposting mitigates landfill trash, reduces methane emissions, and fosters carbon sequestration, in accordance with sustainable development objectives. Operational challenges in vermicomposting include the need to effectively control ideal conditions, the presence of pathogens, and the capacity to scale up the operations.

Vermicomposting is an excellent method for diverting organic waste from landfills, which helps to reduce the release of methane gas and the creation of leachate. This process helps to mitigate environmental damage. Vermicompost treatment enhances soil structure, aeration, water retention, and nutrient availability, hence improving soil health and fertility. Vermicomposting offers a cost-effective and easily accessible method for waste management and sustainable agriculture, helping both rural and urban areas. Vermicomposting adds to climate change mitigation efforts by enhancing carbon absorption and lowering greenhouse gas emissions. Vermicomposting may be easily included in organic farming, therefore decreasing reliance on artificial fertilizers and pesticides and promoting sustainable agricultural methods. In order to fully maximize the benefits of vermicomposting, it is necessary to have policies in place that support it, together with financial incentives and instructional programs that promote its adoption and optimize its practices.

Vermicomposting offers a sustainable and environmentally friendly approach to managing organic waste and improving soil health. The procedure utilizes the inherent ability of earthworms to break down organic waste and transform it into vermicompost, which is rich in nutrients. This method tackles issues related to waste management and enhances the fertility of soil by recycling nutrients and improving microbial activity. Optimizing the quality of vermicompost requires excellent control of environmental conditions, careful selection of suitable raw materials, and the use of different additives and microbial inoculants. In spite of the advantages it offers, vermicomposting encounters obstacles such as the existence of pathogens, difficulties in scaling up, and operational concerns that must be resolved in order to achieve wider acceptance.

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Chapter 22

Residue to rations: Enhancing livestock nutrition with agricultural byproducts

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Chapter Outline

22.1. Introduction 375
22.2. Application of agro-industrial byproducts in animal diets 376
22.3. Potential limitations of utilizing agro-industrial byproducts in animal nutrition and future perspectives 398
22.4. Conclusions 402
References 402

22.1 Introduction

Urbanization and the continuous increase of the global population have resulted in a high demand for food products. In 2021, only two-thirds of agro-industrial production was consumed as food, while the rest was rejected as residues. As a consequence, a vast amount of agro-industrial byproducts (AIBPs) generated are considered waste and are disposed of in the environment. Food industry processing waste, especially waste generated from fruits, vegetables, cereals, and oil extraction, contain mainly peels, seeds, pulp, stems, and kernels and are rich in nutrients and bioactive compounds (Gómez-García *et al.*, 2021). These byproducts are a valuable source of bioactive molecules, mainly polyphenols, with well-known antioxidant, antimicrobial, immunoregulatory, and anticancer activity (Simitzis, 2017). Hence, they can be reincorporated in the production chain and enhance the nutritional value of the products and the health of the consumer. Moreover, fruit and vegetable waste is rich in fiber and polysaccharides (Maqbool *et al.*, 2023; Nirmal *et al.*, 2023; Vastolo, Calabrò, and Cutrignelli, 2022), while residues of cereal processing and oil extraction contain significant levels of protein and are an excellent source of energy (González-Alvarado *et al.*, 2010).

AIBPs can be added directly to food products during production to enhance dietary content, sensory attributes, and preservation (Simitzis, 2017), but they can also be incorporated into livestock diets. In this way, the benefit is twofold, since the byproducts not only improve the quality of the derived foods but also serve as agents that strengthen the health and welfare status of the animals. Moreover, using AIBPs as feed supplements can improve the fatty acid profile in meat,

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milk, or cheese (Vastolo, Calabrò, and Cutrignelli, 2022). Furthermore, AIBPs induce various health benefits to the animals, such as improved antioxidant and immunoregulatory response and balanced intestinal microbiota, which in turn can increase performance (Simitzis and Goliomytis, 2022) and farmers' profit because AIBPs contribute to low-cost animal diets.

At the same time, by consuming AIBPs, the animals become less dependent on conventional feedstuff like cereals, which can be alternately consumed by humans. Thus, food-to-feed competition can be minimized (Gómez-García *et al.*, 2021). Furthermore, discarding tons of organic waste can be both an environmental and financial issue (Gómez-García *et al.*, 2021). However, by exploiting AIBPs in livestock diets, environmental, economic, and social sustainability may be attained. Additionally, utilization of byproducts as feedstuffs locally may reduce feedstuff imports and consequently transfer and environmental costs are expected to decrease (Simitzis and Goliomytis, 2022). Hence, utilization of AIBPs as animal feed is a sustainable practice since it contributes to the circular economy.

22.2 Application of agro-industrial byproducts in animal diets

Agro-industrial wastes that have been studied as alternatives to commercial feedstuff can be classified into the following five groups (Figure 22.1) based on species and processing:

- Fruits originated from the juicing and canning processing industry. Apples, citrus species, grapes, and pomegranates have been studied extensively and will be analyzed in separate subsections. Some tropical fruits will be analyzed in subsection 2.9. Myrtle, prickly pear, and avocado have also been studied (Amata, 2014).
- Oil production waste, including olive (subsection 2.4), palm (subsection 2.6), soybean, sunflower, coconut, and rapeseed (Vastolo, Calabrò, and Cutrignelli, 2022).
- Cereal milling byproducts, mainly tapioca, wheat, rice, and sesame (Vastolo, Calabrò, and Cutrignelli, 2022; Yafetto, Odamtten, and Wiafe-Kwagyan, 2023).
- Other waste that cannot be classified in the above groups, like sugar beet (subsection 2.7),
- Brewer's grain, winery waste, cocoa, coffee, tea, and pistachio (Simitzis and Goliomytis, 2022; Vastolo, Calabrò, and Cutrignelli, 2022).

22.2.1 Apple pomace (AP)

Apple (*Malus domestica*) processing produces significant amounts of solid wastes (~20–30%), including skin, pulp, and seeds, sometimes referred to as "apple pomace." This byproduct can be utilized in animal diets due to its high concentration of dietary fiber, polyunsaturated fatty acids (PUFAs), and beneficial bioactive components like vitamins, anthocyanins, and phenolic acids. Studies on the use of AP in animal nutrition are summarized in Table 22.1. Many in vivo

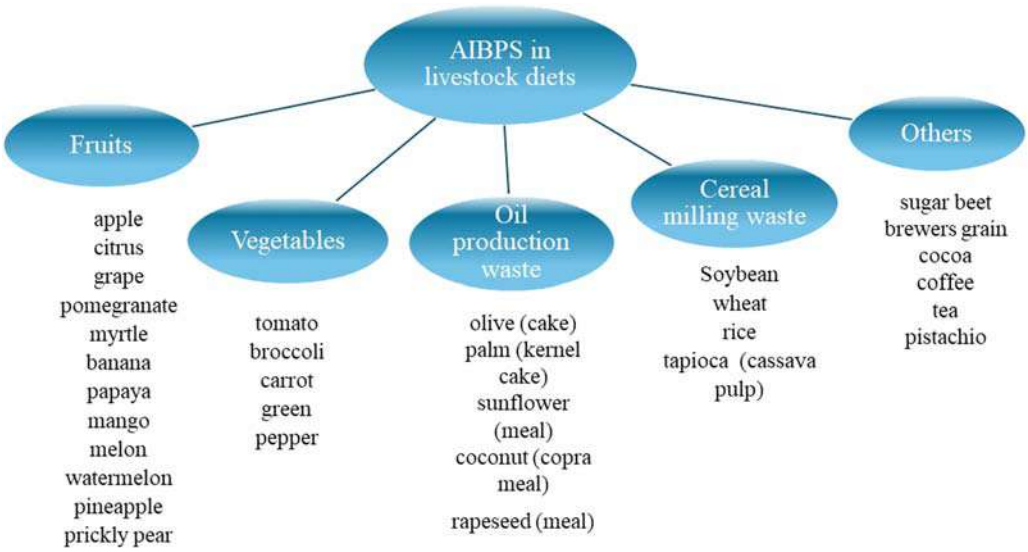


FIGURE 22.1 Categories of agro-industrial byproducts (AIBPS).

TABLE 22.1 Applications of apple byproducts in animal diets.

Species	Form	Level	Results	Reference
Calves	Ensiled	85% (on fresh basis)	Nonsignificant variation in feed efficiency, improved palatability, and increased feed intake and weight gain	(Chauhan *et al.*, 2024)
Dairy cows	Ensiled	15 or 30%	Improved milk yield and dry matter intake	(Azizi *et al.*, 2014)
Dairy cows	Dried	15%	Reduced ammonia concentration and methane emissions, increased nutrient digestibility and milk production	(Gadulrab *et al.*, 2023)
Cows	Dried	0.1 g/kg body weight/day	Lower plasma aminotransferase and glutamate dehydrogenase values related to reduced liver damage	(Stoldt *et al.*, 2015)
Sheep	Dried	11%	Increased yellowness and improved tenderness of meat, decreased meat oxidation during storage	(Alarcon-Rojo *et al.*, 2019)
Pigs	Fermented	2%	Decreased meat moisture and crude protein content, increased pH and water-holding capacity of fresh meat, and improved tenderness, juiciness, flavor, and overall acceptability of cooked meat	(Lee *et al.*, 2009)
Piglets	Dried	8%	Mitigated the negative effects of the Fusarium toxin deoxynivalenol on growth performance	(Gutzwiller *et al.*, 2007)
Breeder roosters	Dried	10, 20, or 25%	Improved sperm characteristics, seminal total antioxidant capacity, fertility, and hatchability rate	(Akhlaghi *et al.*, 2014)
Laying hens	Powder	10% of AP and 0.05% multienzyme supplement	Improved laying hens' performance, egg traits, and blood parameters without any adverse effects	(Ghaemi, Nobakht, and Razzaghzadeh, 2014)
Laying hens	Quercetin powder	0.2, 0.4, or 0.6 g/kg	Improved several aspects of egg quality (eggshell thickness, yolk protein, and cholesterol levels)	(Ying *et al.*, 2015)
Laying hens	Quercetin powder	0.2, 0.4, or 0.6 g/kg	Increased laying rate, Haugh unit, eggshell strength, eggshell thickness, and yolk protein, decreased feed–egg ratio and yolk cholesterol at the end of the peak laying period	(Liu *et al.*, 2013)
Laying hens	Quercetin powder	0.2, 0.4, or 0.6 g/kg	Improved performance by modulation of intestinal environment and liver superoxide dismutase (SOD)	(Liu *et al.*, 2014)
Broilers	Quercetin powder	50–600 mg/kg body weight/day	No significant effect on weight gain or feed intake	(Rupasinghe *et al.*, 2010)
Broilers	Quercetin powder	0.5 or 1 g/kg	Reduced lipid oxidation and increased relative heart weight	(Goliomytis *et al.*, 2015)
Broilers	Quercetin powder	0.1, 0.2, or 0.3 g/kg	Improvement of oxidative stability, color, texture, and sensory characteristics of nuggets	(Sohaib *et al.*, 2015)
Broilers	Quercetin powder	0.1, 0.2, or 0.3 g/kg	Increased oxidative stability, color, texture, and sensory characteristics of nuggets and breast	(Sohaib *et al.*, 2016)

studies have been performed with quercetin as a feed supplement, a flavonol found in apple skin that can enhance the quality of animal-derived products (Pieszka *et al.*, 2015).

Adding 2% fermented AP enhanced growth performance and feed intake and improved carcass traits (Lee *et al.*, 2009) in finishing pigs. Incorporating 3.5% apple pomace in the diet of piglets improved villi morphology, gut-associated lymphoid tissue activation, intestinal flora, blood parameters, and immunoregulatory parameters, resulting in a significant improvement in health status.

In dairy cows, adding AP rations (15−30%) enhanced milk yield and dry matter intake (Azizi *et al.*, 2014; Gadulrab *et al.*, 2023) and had positive effects on liver health (Stoldt *et al.*, 2015). In sheep, AP improved meat oxidative stability (Alarcon-Rojo *et al.*, 2019). Similar results were observed in broilers. In laying hens, up to 10% AP improved both performance and egg quality traits (Ghaemi, Nobakht, and Razzaghzadeh, 2014).

As indicated in Table 22.1, adding quercetin to poultry rations can improve laying rate and feed-egg ratio while increasing Haugh units (Liu *et al.*, 2013) and egg quality traits such as eggshell thickness, egg yolk protein, and cholesterol levels (Ying *et al.*, 2015). In another study, quercetin supplementation did not affect egg quality, but laying hens' performance, intestinal environment, and liver superoxide dismutase content were improved (Liu *et al.*, 2014).

Rupasinghe *et al.* (2010) found that quercetin dietary supplementation at 32 days of age had no impact on weight gain or feed intake in broilers. However, quercetin can extend meat shelf life and improve animal health by reducing lipid oxidation and increasing heart weight (Goliomytis *et al.*, 2014) and ameliorate color, texture, and sensory characteristics of nuggets (Sohaib *et al.*, 2016) and breast (Sohaib *et al.*, 2015).

Quercetin's bioavailability in cows is low due to ruminal microbiota degradation (Berger *et al.*, 2012) and does not affect gas and methane production or ruminal concentrations of volatile fatty acids (Berger *et al.*, 2015). Duodenal administration enhances quercetin aglycone bioavailability, with a positive effect on metabolic adaptation in high-yielding cows to early lactation. Subsequently, quercetin supplementation in periparturient dairy cows for six weeks exerted hepatoprotective potential, as indicated by reduced plasma aminotransferase and glutamate dehydrogenase values (Stoldt *et al.*, 2015).

22.2.2 Citrus pulp (CP)

The main fruit of the citrus (*Rutaceae*) family that is cultivated worldwide is the sweet orange (*Citrus sinensis*) (67.8% of world citrus production) (USDA/FAS, 2024). According to USDA/FAS (2024) statistics, the 2023−2024 forecast for total global production of sweet orange is 48.8 million tons. Brazil is the global production leader with 16.5 million tons, followed by China (7.63 million tons) and Europe (5.48 million tons). CP is the main byproduct of the citrus industry (Bampidis and Robinson, 2006). It is produced after the extraction of the juice and corresponds to approximately 25% of the initial fresh fruit. CP is rich in fiber, protein, and calcium and contains polyphenols, mainly hesperidin and naringin, with antioxidant, antimicrobial, and anti-inflammatory properties. Data regarding the utilization of CP in animal diets are presented in Table 22.2.

Incorporation of *Citrus sinensis* dried pulp (CSP) in the diet of cows increased the flavanones content of milk, especially hesperetin, when added at 4 kg/day/animal. Santos *et al.* (2014) also observed an increase of the concentration of polyphenols and flavonoids in milk after incorporating 9% or 18% pelleted CSP in the diet. Supplementing cows with *Citrus sinensis* flavonoid extract increased milk yield and lactose level while reducing milk somatic cell count linearly. de Oliveira *et al.* (2022) incorporated CSP or corn into the diet of grazing cattle, at 0.5% of animals' live weight, and since they observed no impact on productivity, they proposed CSP as an alternative feedstuff to corn. In another study, Ítavo *et al.* (2020) reported that substitution of corn silage by ensiled peel *Citrus sinensis* increased the fat content in milk. Moreover, *Citrus sinensis* byproducts can alleviate heat stress in cattle. Havlin and Robinson (2015) observed that highly producing dairy cattle expressed more comfort and lying behaviors in the summer, indicators of reduced heat stress, when supplied with 4 g/day/animal of *Citrus sinensis* extract in the rations. The extract also improved the health of the animals by reducing the total somatic cell count.

CP has been studied also as a feedstuff for beef cattle. As in dairy cows (de Oliveira *et al.*, 2022), it has been suggested as a cost-effective alternative to corn. Abdel Gawad, Mahmoud, and Al Slibi (2013) used ensiled CP as a substitute for corn in the diet of growing bulls, up to 45%. Dry matter intake was reduced, but no difference was observed in average daily intake, nutrient digestibility, or blood parameters. Javed *et al.* (2016) reached the same conclusions after adding up to 20% dried CP in the diet of fattening calves. Villarreal *et al.* (2006) suggested that pelleted CP can be a valuable feedstuff when combined with pasture.

Citrus sinensis dried pulp has also been proposed as a sustainable and low-cost feedstuff for sheep. Incorporation of up to 45% in the diet of growing lambs does not affect average weight gain and final carcass characteristics, whereas the price

TABLE 22.2 Applications of citrus byproducts in animal diets.

Species	Byproduct	Form	Level	Results	Reference
Dairy cows	*Citrus sinensis*	Dried pulp	1 kg/day	No effect on digestibility and rumen function	(Lima *et al.*, 2014)
Dairy cows	*Citrus sinensis*	Dried pulp	9% or 18%	Increase of milk total polyphenols and flavonoids level and improvement of antioxidant capacity	(Santos *et al.*, 2014)
Dairy cows	*Citrus sinensis*	Peel silage	250, 500, or 750 g/kg DM	Decrease of feed take and milk production, increase of fat and protein level at 750 g/kg	(Ítavo *et al.*, 2020)
Dairy cows	*Citrus sinensis*	Pulp-based concentrate	50% on total DM	Dry matter intake and ingestion were increased, milk production and composition were not influenced	(Leite *et al.*, 2017)
Dairy cows	*Citrus sinensis*	Dried pulp	0.5% of live weight	Performance was not altered, digestibility was increased	(de Oliveira *et al.*, 2022)
Dairy cows	*Citrus sinensis*	Extract	4 g/cow/d	Oxidative heat stress was decreased, performance was not altered	(Havlin and Robinson, 2015)
Beef cattle	*Citrus sinensis*	Pulp	5, 10, 15, and 20% dried citrus pulp	No effect on growth, blood metabolites, reduction in price per kg diet	(Javed *et al.*, 2016)
Beef cattle	*Citrus sinensis*	Pulp silage	30, 45%	No effect on nutrient digestibility, performance, blood parameters	(Abdel Gawad, Mahmoud, and Al Slibi, 2013)
Beef cattle	*Citrus sinensis*	Pulp pelleted	1.25–2.5 kg/ animal/day	Beneficial when combined with forages high in rumen degradable protein	(Villarreal *et al.*, 2006)
Sheep	*Citrus sinensis*	Peel powder	Citrus peel powder 2.25% or 4.5% DM of basal feed	Increase of weight gain, no impact on body score	(Haryoko *et al.*, 2023)
Sheep	*Citrus sinensis*	Dried pulp	24–35%	Improved meat oxidative capacity and PUFAs level	(Inserra *et al.*, 2014)
Sheep	*Citrus sinensis*	Dried pulp	24–35%	Increased intramuscular PUFAs level	(Gravador *et al.*, 2014)
Lambs	*Citrus sinensis*	Dried pulp	30–45%	No effect on growth and carcass traits	(Caparra *et al.*, 2007)
Lambs	*Citrus sinensis*	Dried pulp	30–45%	No effect on feed intake and carcass traits	(Scerra *et al.*, 2001)
Lambs	*Citrus sinensis*	Dried pulp	30–45%	No effect on growth and carcass traits	(Lanza *et al.*, 2015)
Lambs	*Citrus sinensis*	Dried pulp	30% forages and 70% concentrate 10–40% CP	No effect on average daily gain and digestibility, decrease in price per kg of feed	(Sharif *et al.*, 2018)
Lambs	*Citrus sinensis*	Hesperidin	1.5–3 g/kg	Increase of meat antioxidant capacity during storage, no effect on performance and carcass traits	(Simitzis *et al.*, 2013)
Goat kids	*Citrus sinensis*	Dehydrated citrus pulp	25, 50, and 75% levels	Daily gain, feed intake, and feed conversion were improved	(Bueno *et al.*, 2002)
Goat	*Citrus sinensis*	Pulp	10–50%	More efficient when 50% in the diet	(Oni *et al.*, 2008)

Continued

TABLE 22.2 Applications of citrus byproducts in animal diets.—cont'd

Species	Byproduct	Form	Level	Results	Reference
Growing pig	*Citrus sinensis*	Ensiled pulp	5–10%	No effect on back-fat thickness, meat color, and fatty acids profile	(Cerisuelo *et al.*, 2010)
Growing pig	*Citrus sinensis*	Dried pulp	1 kg/ animal	Increase of PUFAs in longissimus lumborum	(Chiofalo *et al.*, 2007)
Growing pig	*Citrus sinensis*	Dried pulp	15%	No effect on carcass traits and meat quality	(Crosswhite *et al.*, 2013)
Growing pig	*Citrus sinensis*	Dried pulp	10–30%	Negative linear effect on carcass yield and meat color	(Watanabe *et al.*, 2010)
Growing pig	*Citrus sinensis*	Ensiled pulp	0, 50, 100, and 150 g/kg diet on dry matter base	No impact on nutrient digestibility, carcass yield, fatty acids profile	(Moset *et al.*, 2015)
Broiler	*Citrus sinensis*	Peel extract	1.5 or 3%	No influence on final weight and carcass yield—increase of FCR and decrease in feed intake and body weight gain during the starter and grower period at 3%	(Ebrahimi *et al.*, 2013)
Broiler	*Citrus sinensis*	Peel extract	1.25 g/kg (1000–1,250 ppm)	Reduced abdominal fat content, no effect on carcass weight	(Ebrahimi *et al.*, 2014)
Broiler	*Citrus sinensis*	Dried pulp	10%	Negative effect on performance but increase in PUFAs level	(Mourão *et al.*, 2008)
Broiler	*Citrus junos*	Byproducts fermented with probiotics	5–20 g/kg	Improved immunity and reduced lipid peroxidation	(Ahmed *et al.*, 2014)
Broiler	-	Naringin	0.7–1.5 g/kg	Improved meat oxidative stability	(Goliomytis *et al.*, 2015)
Broiler	-	Hesperidin	5, 10, 15, 20 mg/kg	Positive influence on fatty acids profile	(Kamboh and Zhu, 2013a)
Broiler	-	Hesperidin	5, 10, 15, 20 mg/kg	Positive impact on water-holding capacity and lipid oxidative stability	(Kamboh and Zhu, 2013b)
Broiler	Orange or lemon	Peel extract	200 mg/g	Increased serum total protein, no effect on growth	(Akbarian *et al.*, 2013)
Broiler	*Citrus sinensis*	Extract	1000–2000 mg/L	Improved immune system response	(Pourhossein *et al.*, 2015)
Broiler	*Citrus sinensis*	Dried pulp	0.5–2%	Weight gain was improved, but FCR not altered	(Abbasi *et al.*, 2015)
Broiler	*Citrus sinensis*	Peel dried	0.80%	Decrease of serum cholesterol, low- and high-density lipoproteins and triglycerides level, improvement of antioxidative stability	(Alzawqari *et al.*, 2016)
Broiler	Lime (*Citrus aurantifolia*)	Dried pulp	2.5–12%	Decrease of weight gain and FCR, decreased antibody titers against influenza disease at 7.5%	(Basir and Toghyani, 2017)

Laying hen	*Citrus sinensis*	Dried pulp	12%	No adverse effect on performance and egg quality in the early phase of production	(Nazok, Rezaei, and Sayyahzadeh, 2010)
Laying hen	*Citrus sinensis*	Dried pulp	9%	Improved egg yolk oxidative stability but reduced performance and egg quality	(Goliomytis *et al.*, 2018)
Laying hen	-	Hesperidin	1−3 g/kg	Improved egg yolk oxidative stability	(Goliomytis *et al.*, 2015)
Laying hen	-	Hesperidin/naringenin	0.5, 1, 2, and 4 g/kg	Lower serum and egg yolk cholesterol, enhanced antioxidant capacity	(Ting, Yeh, and Lien, 2011)
Laying hen	-	Hesperidin/naringenin	0%	Reduced egg and serum yolk cholesterol level	(Lien, Yeh, and Su, 2008)
Duck	*Citrus aurantium*	Dried peel extract	200 mg hesperidin/ kg feed	Antioxidant effect on meat	(Marzoni *et al.*, 2014)
Geese	*Citrus sinensis*	Dried pulp	0, 4, 8, 12, or 16% DCP	No effect on growth performance and carcass yield when less at 12%	(Wang *et al.*, 2017)
Ostrich	*Citrus sinensis*	Pulp	20%	Reduction of meat cooking loss and increase of PUFAs	(Lanza *et al.*, 2004)
Laying Quail	*Citrus sinensis*	Dried pulp	0, 3, 6%	Average egg weight was increased	(Botsoglou *et al.*, 2004)

of feed per kg was reduced. Additionally, incorporating 20 to 35% CP in the rations can enhance the oxidative stability of the meat and increase the level of PUFAs. Moreover, the use of hesperidin as a feed additive in the diet of lambs can improve the oxidative status of meat during storage. As far as the authors are aware, two studies have been performed on goats. Oni *et al.* (2008) studied the use of dried CP as a feedstuff for African dwarf goats. Growth rate, nutrient digestibility, and various blood parameters were improved. Bueno *et al.* (2002) used dried CP as a feedstuff in high percentages (25−75%) in the nutrition of Saanen goats, and they determined increased feed intake and daily weight gain.

In pigs, the results are contradictory. Incorporation of 5 to 10% or 15% dried CP (Crosswhite *et al.*, 2013) had no effect on carcass traits, meat sensory characteristics, or fatty acids profile (Cerisuelo *et al.*, 2010). Nonetheless, adding 1 kg/animal in the diet resulted in an increase of the level of PUFAs in the *Longissimus lumborum* muscle. In another study, Moset *et al.* (2015) observed that inclusion of ensiled CP up to 100 g/kg diet had no effect on nutrient digestibility, carcass yield, or the profile of lipids of the subcutaneous fat. Furthermore, the inclusion of citrus byproduct in the rations led to a decrease of enterobacterial counts in the feces. A higher percentage than 30% of CP in the rations negatively affected growth, carcass yield, and meat color. Not only CP but also *Citrus sinensis* extract has been researched as a feed additive for growing pigs. Adding 0.25 ml/kg diet ameliorated the oxidative properties of meat and increased the intramuscular fat content, although not affecting growth performance.

The valorization of *Citrus sinensis* peel as a feedstuff for broilers has been extensively studied. Dried citrus peel did not affect feed intake (Alzawqari *et al.*, 2016), feed conversion ratio (FCR), or carcass traits (Alzawqari *et al.*, 2016) but decreased body weight gain when used more than 20% in the diet of broilers. According to Alzawqari *et al.* (2016), using only 0.8% in the diet resulted in decreased concentration of cholesterol and serum triglycerides, and the antioxidant properties of meat were improved. Incorporation of peel extract instead of dried peel at 3% also resulted in reduction of cholesterol and triglycerides level but decreased feed intake, although not affecting the final weight of the birds (Ebrahimi *et al.*, 2013). Adding lemon (*Citrus aurantifulia*) peel extract at 200 mg/g increased total serum protein concentration and weight gain (Akbarian *et al.*, 2013). On the contrary, lime-dried pulp in the diet had an adverse effect on final body weight, FCR, and broilers' immune response (Basir and Toghyani, 2017). A high percentage of *Citrus sinensis* dried pulp (10%) also had negative effects on final weight and feed intake. Contrariwise, low concentrations (0.5−2%) improved weight gain and feed intake and ameliorated immune response. Using *Citrus junos* byproducts fermented with probiotics also improved immunity and reduced lipid oxidation by reducing thiobarbituric acid reactive substance levels. Furthermore, inclusion of hesperidin in the rations improved meat lipid profile and water-holding capacity. Inclusion of naringenin improved meat oxidative stability as well.

As for meat in broilers, incorporation of naringenin in the diets of laying hens improves the oxidative stability of the eggs. Productivity and egg quality were not affected, but serum and egg yolk cholesterol levels were reduced.

Citrus sinensis pulp byproducts also have been evaluated in the diet of other poultry species. Dried CP in the diet of ostriches reduced meat water cooking loss and positively altered the profile of PUFAs. Incorporation of up to 12% in the rations of geese did not impair growth performance or carcass yield but decreased FCR. In quails, there was no influence on egg productivity, but it increased hatchability and average egg weight. In ducks, the oxidative stability of meat was increased.

22.2.3 Grape pomace (GP)

Grape pomace, also known as marc, is produced by destemming, crushing, and pressing grapes. It consists mostly of peels, stems, and seeds and accounts for around 20% of the weight of grapes processed into wine. It contains a variety of polyphenols, i.e., high-value molecules with antioxidant, anti-inflammatory, anticancer, antimicrobial, cardioprotective, neuroprotective, and hepatoprotective properties. Grape byproducts are increasingly used in the food industry as an alternative to chemical antioxidants to inhibit lipid oxidation during refrigerated and frozen storage and extend meat product shelf-life.

In ruminants, GP can ameliorate rumen conditions and positively affect bacteria population (Table 22.3). Feeding dairy cows 5 kg GP per day can reduce methane emissions by 20%. Conversely, when added up to 75% in sheep diet, GP can negatively impact rumen parameters such as pH, ammonia, and bacteria population. Ruminants' diets containing up to 450 g/kg GP also showed decreased protein digestibility, ammonia, and volatile fatty acids production (Besharati and Taghizadeh, 2009).

GP, up to 10%, can be beneficial in fattening lambs' diet without affecting their growth (Bahrami *et al.*, 2010) and simultaneously can improve meat oxidative stability and fatty acids composition (Bennato *et al.*, 2023). Higher inclusion than 10% can induce negative effects on meat quality (Antunović *et al.*, 2023). According to Jerónimo *et al.* (2012), adding grape seed extract (25 g/kg of dry matter) to lamb diets did not affect meat fatty acid profile. However, grape marc in ewe

TABLE 22.3 Applications of grape byproducts in animal diets.

Species	Byproduct	Form	Level	Results	Reference
Ruminants	Grape pomace	Dried	up to 450 g/kg	Reduced protein digestibility, ruminal ammonia, and volatile fatty acids production	(Besharati and Taghizadeh, 2009)
Cows	Grape pomace	Dried	5 kg	Decreased methane emissions and yield	(Moate *et al.*, 2014)
Bulls	Grape pomace	Ensiled	10% and 20%	Decreased urinary nitrogen levels, increased total antioxidant capacity	(Li *et al.*, 2024)
Steers	Grape pomace	Dried	100 g/kg	Improved antioxidant capacity and immune response	(Molosse *et al.*, 2023)
Sheep	Grape pomace	Dried	1% and 2%	Increased the abundance of beneficial rumen microflora	(Rolinec, 2022)
Lambs	Grape pomace	Dried	10%	Improved meat oxidation stability	(Bennato *et al.*, 2023)
Lambs	Grape pomace	Dried	10%	No negative effects on growth	(Bahrami *et al.*, 2010)
Lambs	Grape pomace	Dried	25 g/kg	Enhanced protection against lipid peroxidation	(Jerónimo *et al.*, 2012)
Lambs	Grape pomace	Dried	25 g/kg	Meat fatty acid profile was not modified	(Jerónimo *et al.*, 2010)
Lambs	Grape pomace	Extract	2.5%	Reduced lipid autoxidation rate	(Vasta *et al.*, 2010)
Lambs	Grape pomace	Extract	Polyphenols (900 ppm)	Improved meat oxidative stability	(Rivas-Cañedo *et al.*, 2013)
Lambs	Grape pomace	Dried	10% and 20%	Negative effects when used more than 10%	(Antunović *et al.*, 2023)
Sheep	Grape pomace	Dried	75%	Negative effects on rumen parameters	(Abarghuei, Rouzbehan, and Alipour, 2010)
Pigs	Gape pomace	Fermented	30 g/kg	Increased marbling score, meat color, and oxidation stability	(Yan and Kim, 2011)
Pigs	Grape seed	Flavonoids extract	2 g/kg	Decreased meat lipid oxidation values	(González and Tejeda, 2007)
Pigs	Grape pomace	Fermented	30 g/kg	Improved growth performance, nutrient digestibility, and modified fatty acid pattern	(Yan and Kim, 2011)
Pigs	Grape seed	Extract	100 or 300 or 700 mg/kg	No effect on lipid peroxidation of longissimus dorsi muscle	(O'Grady *et al.*, 2008)

Continued

TABLE 22.3 Applications of grape byproducts in animal diets.—cont'd

Species	Byproduct	Form	Level	Results	Reference
Finishing pigs	Grape pomace	Fermented	0.3 or 0.6 g/kg	Decreased body fat deposition	(Zhang *et al.*, 2015a)
Finishing Pigs	Grape pomace	Dried	2.5%	Improved carcass weight and loin area and decreased marbling	(Ospina-Romero *et al.*, 2023)
Finishing pigs	Grape pomace	Dried	6%	Enhanced anti-inflammation status, gut barrier function, and meat quality	(Tian *et al.*, 2023)
Finishing pigs	Grape pomace	Fermented	300, 600 mg/kg	Increased meat oxidation stability	(Zhang *et al.*, 2015b)
Broilers	Grape pomace	Dried	5 and 10%	Reduced lipid peroxidation and increased PUFAs level	(Chamorro *et al.*, 2015)
Broilers	Grape pomace	Dried	5, 15, and 30 g/kg	Increased the antioxidant capacity of breast muscle	(Goñi *et al.*, 2007)
Broilers	Grape pomace	Dried	15, 30, or 60 g/kg	Increased the antioxidant capacity of breast muscle, growth performance was not altered	(Brenes *et al.*, 2008)
Broilers	Grape seed	Dried	0%, 3%, and 6%	Positive changes in blood parameters	(Mauro *et al.*, 2023)
Broilers	Grape seed	Extract	7.2 g/kg	Modified the gut morphology and intestinal microflora	(Viveros *et al.*, 2011)
Broilers	Grape pomace	Dried	2.5%, 5%, and 7%	Meat drip loss, yellowness, redness, and fatty acid profile were improved	(Bennato *et al.*, 2020)
Laying hens	Grape pomace	Dried	4–6%	Increased egg productivity, liver weight, and antioxidation capacity of eggs	(Kara *et al.*, 2016)
Quails	Grape pomace	Resveratrol extract	400 mg/kg	Enhanced antioxidant status of birds and eggs	(Sahin *et al.*, 2010)

diets increased cis-9, trans-11 conjugated linoleic acid, and vaccenic acid content in milk. Moreover, grape seed extract protects sheep meat against lipid oxidation. Ensiled GP improved the antioxidant status and immune system of steers while not affecting productivity. A study on Angus bulls showed that incorporating dried GP dry matter into their diet led to higher average daily gain and total antioxidant capacity.

Dietary supplementation with 30 g/kg fermented GP showed improvements in growth performance, nutritional digestibility, subcutaneous fatty acid pattern, and meat quality in pigs. GP has been found to improve gut barrier function, meat quality, and growth performance in finishing pigs. Furthermore, combining ferulic acid and GP in finishing pigs' diets improved carcass weight and loin area and decreased marbling. Adding flavonoids from grapes (2 g/kg) to Iberian pig diets reduced lipid peroxidation. On the contrary, supplementing pig diets with grape seed extract (100, 300, or 700 mg/kg) had no effect on lipid oxidation rates in the longissimus dorsi muscle.

In broilers, supplementation with GP up to 60 g/kg boosted antioxidant levels in meat (Brenes *et al.*, 2008). Both GP and seed extract modified gut morphology and increased intestinal microflora biodiversity. Chamorro *et al.* (2015) found that adding phenolic compounds from grape pomace to broilers' diet reduced lipid oxidation and boosted PUFA content without negatively impacting body weight or feed efficiency. Bennato *et al.* (2020) also observed that GP can improve meat drip loss, yellowness, and redness. Using grape byproducts as functional feed supplements can extend meat shelf-life (Alfaia *et al.*, 2022; Bennato *et al.*, 2020). Furthermore, incorporating both GP and grape seeds in the ratios of broilers improved the immune response of the birds.

Adding 4 or 6% GP to the diet of laying hens had no significant effect on productivity but increased egg weight and egg yolk oxidation stability. Resveratrol, a polyphenol from red grapes, has been found to improve the antioxidant status of birds and eggs when added to quail diets up to 400 mg/kg.

22.2.4 Olive cake (OC)

Olive oil, originated from the *Olea europaea* tree, is one of the most important and beneficial ingredients of the Mediterranean diet. It is rich in phenolic compounds with strong antioxidant activity that induce various benefits in human health, like reduction of cholesterol and strengthening of cardiovascular health. The main producers of olive oil on a global basis are Spain, Italy, and Greece. The production in these countries, in 2021, reached 1,492,339 and 293 tons, respectively. Since the production of 1 kg of olive oil generates approximately 800 g of byproducts, with olive cake being the main one (Camposeo, Vivaldi, and Gattullo, 2013), hundreds of tons of waste related to olive oil production are produced every year, which can be used, among others, as alternative feedstuffs.

The inclusion of OC has been studied in the diets of various ruminants, as presented in Table 22.4, since it is rich in fiber (23−73%) and low in protein (8−11%). There was no effect on milk yield when it was incorporated up to 15% on a dry matter basis in the rations of dairy cattle (Castellani *et al.*, 2017) or buffaloes. Nonetheless, in cows, it increased the level of monounsaturated fatty acids (MUFAs) and especially oleic acid (Castellani *et al.*, 2017) and polyunsaturated fatty acids in both milk and cheese, and it decreased the atherogenic and thrombogenic indices of cheese. Gene expression related to mammary and adipose lipid metabolism was not altered. In Limousin bulls, final body weight and carcass traits were ameliorated. Moreover, supplementation of 0.5% dried OC to beef cattle until slaughter increased meat oxidative stability while prolonging color deterioration and inhibiting the development of smell during storage (Branciari *et al.*, 2015).

In dairy ewes, as in cows (Castellani *et al.*, 2017), supplementation up to 20% of partly destoned or ensiled (Cabiddu *et al.*, 2004) OC did not alter performance. Still, it improved the quality of the milk by increasing the unsaturated/saturated fatty acids ratio, reducing atherogenic indices, and enhancing antioxidant capacity. The lipid profile and atherogenicity of derived cheese were also altered positively. In lactating goats, concentrated feed supplement with exhausted OC or mixed and ensiled with sunflower oil (Arco-Pérez *et al.*, 2017) increased the milk content in polyunsaturated fatty acids. Additionally, ensiled OC as a sole concentrated feedstuff also increased the milk content in protein, fat, MUFAs, and PUFAs, reducing atherogenicity and thrombogenicity indices. Moreover, OC has been proposed as a cost-effective feedstuff for mature rams, since it does not impair sperm quality and reproductive performance.

Utilization of OC as a feedstuff for fattening lambs, up to 30% on a dry matter basis, did not influence either growth performance (Awawdeh and Obeidat, 2011; Ben Salem and Znaidi, 2008) or carcass weight. Regarding carcass traits, meat content in fat and proteins was reduced, and subcutaneous fat content was altered. However, in another study, the PUFAs level was not influenced by OC supplementation. All the summarized studies in Table 22.4 recommend OC as an alternative feedstuff for lambs that can ensure performance and reduce feed cost. As analyzed by Ben Salem and Znaidi (2008), using feed blocks that contained 44% OC resulted in 75% reduction of conventional concentrate feed.

In growing pigs, incorporating up to 40% OC on a dry matter basis does not affect growth. The ensiled OC improved the nutritional value of pork meat since it increased MUFA and PUFA levels, and thus contributed to a fatty acids profile

TABLE 22.4 Applications of olive byproducts in animal diets.

Species	Byproduct	Form	Level	Results	Reference
Ewes	Olive cake	Partly destoned	20%	Increased milk yield, nutritional traits, and unsaturated/saturated fatty acid ratio, decreased atherogenic and thrombogenic indices	(Chiofalo *et al.*, 2004)
Ewes	Olive cake	Silage	100 g/kg as a replacement for grass hay	No effects on milk yield and composition	(Cabiddu *et al.*, 2004)
Ewes	Olive cake	Partly destoned	98–244 g/kg	Improved antioxidant capacity and fatty acids profile of milk	(Vargas-Bello-Pérez *et al.*, 2013)
Ewes	Olive cake and tomato pomace	Dried	2–5 kg dry matter/day	Nutritional composition of yogurt and cheese was not modified	(Abbeddou *et al.*, 2011)
Ewes	Olive cake	Ensiled	10–20%	No effect on milk yield and composition, increase in MUFAs, PUFAs, reduction in atherogenic and thrombogenic traits	(Symeou *et al.*, 2021)
Lambs	Olive cake	Dried	12%	Performance was not altered	(Awawdeh and Obeidat, 2011)
Lambs	Olive cake	Feed blocks	44%	No impact on performance	(Ben Salem and Znaidi, 2008)
Lambs	Olive cake	Dried	15%	Decreased muscle content of fat and proteins, no effect on daily gain, carcass weight, dressing percentage	(Mioč *et al.*, 2007)
Lambs	Olive pulp	Ensiled	Up to 30%	No effect on carcass characteristics and major cuts	(Taheri *et al.*, 2012)
Lambs	Olive cake	Dried	320 g/kg	Reduced palmitic, increased oleic and stearic acid levels	(Vera *et al.*, 2009)
Lambs	Olive cake	Dried	35%	No impact on PUFAs level	(Mele *et al.*, 2014)
Lambs	Olive cake	Dried	17 and 35% (with 20 and 10% linseed, respectively)	Reduced cholesterol, increased meat antioxidant capacity	(Luciano *et al.*, 2013)
Goats	Olive cake	Exhausted	80 g/kg	Higher PUFAs and linoleic acid	(Marcos *et al.*, 2020)
Goats	Olive cake	Ensiled with sunflower oil	200 g/kg	No effect on milk yield, composition, or ruminal fermentation, increased energy balance and microbial protein synthesis	(Arco-Pérez *et al.*, 2017)
Goats	Olive cake	Ensiled	10–20%	No effect on milk yield, improved milk fat and protein content, increased MUFAs, PUFAs	(Neofytou *et al.*, 2023)
Dairy cattle	Olive cake	Dried, partially destoned	15%	No effect on milk yield and cheese chemical profile, increased MUFAs, PUFAs, and oleic acid levels, decreased cheese atherogenic and thrombogenic indices	(Chiofalo *et al.*, 2020)

Dairy cattle	Olive cake	Dried	10%	No effect on milk yield, increase in protein content, increased MUFAs, oleic acid	(Castellani *et al.*, 2017)
Dairy cattle	Olive cake	Ensiled	10%	No effect on milk yield, increased milk fat yield, MUFAs, PUFAs, oleic acid and levels, in both milk and halloumi cheese, reduced atherogenic and thrombogenic indices	(Neofytou *et al.*, 2020)
Dairy cattle	Olive cake	Ensiled	10%	No effect on milk yield, protein, and fat content, increase in milk fat yield and MUFAs level in milk	(Neofytou *et al.*, 2021)
Beef	Olive cake	Dried, partially destoned	7.5–15%	Increased weight gain, intramuscular fat content, PUFAs, MUFAs level, and meat yellowness, reduced meat cooking loss, shear force value	(Chiofalo *et al.*, 2020)
Beef	Olive cake	Dried	50%	Reduced lipid peroxidation, retarded meat color deterioration and odor development during storage	(Branciari *et al.*, 2015)
Beef	Olive cake	Dried	50%	Reduced lipid peroxidation, retarded meat color deterioration and odor development during storage	(Branciari *et al.*, 2015)
Buffaloes	Olive cake	Dried, stoned	15.5% as a replacement for concentrates	No effect on milk yield, milk composition, and coagulation parameters	(Terramoccia *et al.*, 2013)
Rabbits	Olive cake	Meal	Olive cake meal (OCM) at 10% and 20% with or without citric acid at levels 0.1 % or 0.2 %	Increased weight gain, feed intake, economic efficiency, performance index, improved FCR, decreased cholesterol and triglycerides	(Azazi *et al.*, 2018)
Pigs	Olive cake	Dried	50–150 g/kg	No effects on carcass and meat characteristics	(Joven *et al.*, 2014)
Pigs	Olive cake	Ensiled	20–40% on dry matter basis	No impact on performance and proximate meat analysis results	(Caparra *et al.*, 2023)
Broilers	Olive cake	Dried	57 g/kg	Increased MUFAs levels, decreased PUFAs and cholesterol in egg yolk	(El-Samee and Hashish, 2011)
Broilers	Olive cake or olive leaves	Dried	5–10% olive leaves or cake	No effect on the growth and mineral content in femur, tibia, and humerus	(Pečjak *et al.*, 2020)
Broilers	Olive cake	Dried	5–10%, with or without yeast (*Saccharomyces cerevisiae*) at 0.2–0.4 g/kg.	No alteration of carcass traits and internal organs	(Al-Harthi, 2016)
Broilers	Olive cake	Dried	2–4% with or without *Bacillus licheniformis*	Improved nutrient and fat utilization, performance and antioxidative capacity, titers against Newcastle disease, decreased total cholesterol	(Saleh, Paray, and Dawood, 2020)
Laying hens	Olive cake	Dried	10–20% and citric acid 0.1–0.2%	Increased feed intake, decreased FCR	(Al-Harthi and Attia, 2015)
Laying hens	Olive cake	Dried	10–20% and *Saccharomyces cerevisiae* 0.02–0.04%	Increase in feed intake, decreased FCR	(Al-Harthi, 2015)
Quails	Olive cake	Dried	5–7.5%	Decrease in serum total cholesterol, muscle PUFAs levels, increase in MUFAs level in breast	(Özcan *et al.*, 2021)

that is healthier for the consumer. An increment in both subcutaneous mono- and polyunsaturated fatty acids levels in pork meat after supplementation with 12% partially defatted OC. Inclusion of 10% OC combined with 0.1% citric acid in the rations of fattening rabbits improved daily weight gain and meat antioxidant capacity but impaired FCR.

Enrichment of broilers' diet with up to 10% OC had no effect on growth performance (El-Samee and Hashish, 2011) but decreased cholesterol and increased PUFAs content while mineralization was maintained unchanged. Because the fiber content of olive byproducts is high, addition of yeast (Al-Harthi, 2016) or bacteria may improve nutrient utilization by poultry, as indicated in Table 22.4; observations of laying hens also show that adding yeast (Al-Harthi, 2015) or citric acid (Al-Harthi and Attia, 2015) in the diet increased feed intake and reduced FCR without affecting egg productivity. On the other hand, using more than 4% dried OC in the rations of layers decreased productivity. Finally, up to 7.5% OC in the rations of quails had a positive effect on meat quality.

22.2.5 Pomegranate pulp (PP)

According to the United Nations Economic Commission for Europe (2024), cultivation of pomegranate trees is growing rapidly; today an exciting 300,000 ha on a global basis. India and China are the global leading producers of pomegranate fruits (*Punica granatum* L.). In Europe, the main producer is Spain, producing around 50,000 tons annually. This high production is a result of the widespread popularity of the fruit due to its properties against various diseases, even cancer. Moreover, it is rich in vitamin E and polyphenolic bioactive compounds, with strong antioxidant and antimicrobial properties. These compounds also exist in the pomegranate byproducts, the main ones being peel and seed pomace.

As presented in Table 22.5, most of the studies referring to the use of PP as livestock feedstuff have been performed on ruminants. After the incorporation of fresh and ensiled PP into the diet of lactating cows (8% on dry matter basis), milk yield was decreased but the fat content of the milk was increased. Meanwhile, using 8% ensiled pomegranate pulp impairs the performance of the animals, and it should be lowered to 4%. This conclusion is in contrast to the observations of Khorsandi *et al.* (2019), who incorporated up to 18% pomegranate pulp on a dry matter basis in the rations and reported that using up to 12% increased milk yield in lactating cows under heat stress, although milk lactose and protein content was decreased. In this study, the pulp was also ensiled and used as a replacer of corn. Another study used up to 4% peel extract in the diet of dairy cows and observed that both milk yield and milk energy corrected yield were improved. The addition of dried pomegranate peel improved antioxidant capacity and immunity indices of cows' blood serum. Furthermore, using even 0.4 mL/day of peel extract in the diet of lactating cows decreased blood cholesterol (Abarghuei *et al.*, 2014). PP byproducts can be additionally combined with other nutrients to enhance their activity. The incorporation of 8.8% pomegranate pulp into the diets of primiparous cows enriched with fish oil or palmitic acid to examine if the pulp can promote the antioxidant effect of the diets. In both cases, feed intake and antioxidant capacity of the animals were improved. In beef cattle, providing ad libitum fresh pomegranate resulted in increased plasma alpha-tocopherol and improved growth performance.

The observations of sheep indicate that PP can be used in the rations at a higher percentage, without impairing performance. Valenti *et al.* (2019) replaced up to 68.4% of corn and barley-based rations with PP in the diets of ewes in the late lactation period. Although milk yield was not affected, milk quality was improved since its total antioxidant capacity was higher. Incorporating up to 31.4% PP in the diet of fattening lambs did not affect carcass weight or characteristics but decreased FCR (Ghoreishi *et al.*, 2021). On the other hand, ensiled pulp should be used up to 20% in the diet of sheep. Still, in this study, the pomegranate byproduct was mixed with soy hulls and corn silage. Natalello *et al.* (2019) using barley and corn and a corn-based diet observed that adding up to 10% pomegranate peel silage to the rations decreased feed intake and growth, but in this case the diet consisted of straw, alfalfa hay, barley, cottonseed cake, barley, and beet silage. Hence, the feedstuffs with which pomegranate pulp is combined are a determining factor for the feed intake. In goats, fortification of the diet with up to 12% pomegranate seed pulp did not affect milk yield; still, it increased milk fat content. Incorporation of pomegranate peels in the rations of Mahabadi kids reduced the level of n-3 PUFAs and ameliorated meat preservation.

Enriching the rations of broilers with 2% PP (Ahmed *et al.*, 2015) or 0.5 to 1.5% pomegranate seed oil altered the fatty acid profile of the meat and increased its PUFA level. Furthermore, lipid oxidation was reduced. Incorporating up to 7% PP in the diet of heat-stressed birds improved birds' growth performance and antioxidant capacity. Not only PP but also pomegranate peel extract (0.5 g/kg) lowers serum total cholesterol level and improves the flavonoid content of milk. In a recent study, meat production slightly decreased, but the quality of meat was improved by reducing lipid peroxidation and PUFA levels in the breast and thigh meat. The production cost was also decreased by 50% compared to using corn silage in the rations. In laying hens, the use of pomegranate seed pulp of up to 15% enhanced egg production (Saki *et al.*, 2014). Additionally, adding 2 to 4% peel to the rations reduced plasma cholesterol and triglycerides levels and ameliorated the

TABLE 22.5 Applications of pomegranate byproducts in animal diets.

Species	Form	Level	Results/Observations	Reference
Lactating cows	Pulp-fresh ensiled	8%	Decreased feed intake and digestibility, increased milk fat level	(Shaani *et al.*, 2016a)
Lactating cows	Pulp	8%	Negative effects on milk yield and quality when more than 4%	(Shaani *et al.*, 2016b)
Lactating cows	Peel extract	1, 2, or 4%	Ruminal microflora was ameliorated, digestibility, milk yield, and energy-corrected milk yield were increased	(Jami *et al.*, 2012)
Lactating cows	Peel extract	0.4, 0.8, or 1.2 mL/day	Reduction of blood cholesterol and urea	(Abarghuei *et al.*, 2014)
Lactating cows	By-products silage fresh ensiled	0, 60, 120, and 180 g PBS/kg dry matter	Increase in milk yield and energy corrected milk but decrease of milk lactose value	(Khorsandi *et al.*, 2019)
Lactating cows	Peel	2, 3, 4%	Milk yield, antioxidant activity, and immune response were higher	(Abbas, Al-Salhie, and Al-Hummod, 2017)
Lactating cows	Pulp	87 g/kg DM (in palmitic acid or fish oil-enriched diets)	Blood inflammatory parameters were altered, antioxidant ability and feed intake were enhanced	(Akhlaghi *et al.*, 2022)
Lactating cows	Pulp	88 g/kg DM (in palmitic acid or fish oil-enriched diets)	Chewing activity was not altered, meal numbers were decreased, and meal duration was increased	(Akhlaghi *et al.*, 2021)
Beef cattle	Fresh peels	ad libitum	Increases in feed intake and plasma accumulation of alpha-tocopherol with positive tendency toward increased weight gain of bull calves	(Shabtay *et al.*, 2008)
Goats	Seed pulp	6 or 12%	Did not affect weight gain or milk yield, milk fat concentration was increased	(Modaresi *et al.*, 2011)
Sheep	Fresh pulp	40%	When lower than 20%, increased digestibility; when higher than 20%, reduced performance	(Shaani *et al.*, 2016a)
Sheep	Pulp	64.8%	Improvement of milk quality, yield not affected	(Valenti *et al.*, 2019)
Lambs	Peels, membranes, seeds, and residual pulp	200 g/kg DM—20%	Carcass weight, feed intake, or the average daily gain not altered; intramuscular fatty acids composition was improved	(Natalello *et al.*, 2019)
Lambs	Pulp (peel and seed)	27.2% or 31.4%	Performance and carcass traits were not affected, increase in kidney fat	(Ghoreishi *et al.*, 2021)
Lambs	Peel silage	5 or 10%	Growth and feed intake were increased	(Moradi *et al.*, 2021)
Broilers	Pulp	2%	Reduction of saturated and increase of monounsaturated fatty acids level, reduction of lipid peroxidation	(Ahmed *et al.*, 2015)
Broilers	Seed oil	0.5–1.5%	The content of PUFAs was increased and MUFAs decreased	(Szymczyk and Szczurek, 2016)
Broilers	Seed extract	200–300 mg/kg	Improvement of the antioxidant capacity and meat quality	(Saleh *et al.*, 2017)

Continued

TABLE 22.5 Applications of pomegranate byproducts in animal diets.—cont'd

Species	Form	Level	Results/Observations	Reference
Broilers	Pulp fermented	1 or 2%	Enhancement of growth performance, and decrease in feed cost per unit of weight gain	(Bostami *et al.*, 2015)
Broilers	Peel extract	0.5−1 g/kg	Improvement of carcass yield and meat phenol and flavonoid concentration, decrease in total cholesterol	(Kishawy *et al.*, 2019)
Broilers	Pulp	40, 70, and 100 g/kg diet	When at 7% increased performance and oxidative status	(Hosseini-Vashan and Raei-Moghadam, 2019)
Laying hens	Seed pulp	up to 15%	Higher egg production and blood cholesterol level	(Saki *et al.*, 2014)
Laying hens	Dried pulp	0, 4, 7, and 10% plus multi-enzyme	Haugh unit, egg weight, yolk cholesterol were decreased when more than 10%, eggshell thickness and resistance and egg yolk lipids were increased	(Hosseini-Vashan and Ghaznavi, 2018)
Quails	Peel powder	2.5−7.5%	Improvement of FCR, egg production, weight and reduction of serum cholesterol	(Abbas, Al-Salhie, and Al-Hummod, 2017)

oxidative stress of the birds during the pre-peak period. Hosseini-Vashan and Ghaznavi (2018) used a mixture of PP with multi-enzymes as feedstuff (up to 10% on a dry matter basis) and observed that the level of egg lipids (including low-density lipoproteins) and egg weight increased. Similar results were reported also for quails (Abbas, Al-Salhie, and Al-Hummod, 2017).

22.2.6 Palm kernel cake

Palm kernel cake (PKC) is the main byproduct of the palm oil extraction from palm trees (Arecaceae family). Palm trees are cultivated in tropical and subtropical countries. Global production is estimated to reach 79.48 tons in 2024. PKC is rich in fiber, sugars, and various minerals but poor in proteins. Still, the chemical composition varies depending on the palm tree species, the origin, and the oil extraction method (mechanical processing or extraction by solvent).

As indicated in Table 22.6, more studies on the use of PKC as a feedstuff have been conducted on ruminants due to its high crude fiber content (6−24.9%). Using up to 15% PKC on a dry matter basis in the diet of lactating cows had an effect on idling and rumination. Dietary rations with up to 75% PKC for dairy cows kept on pasture resulted in decreased feed intake and digestibility of total crude protein and non-fibrous carbohydrates. However, inclusion of the same PKC percentage in the diet had no impact on milk yield and chemical composition. Still, the PKC level in the concentrated feed was high in the aforementioned two studies, up to 75%. In beef cattle, a feed supplement that included up to 16% PKC positively influenced the performance of feedlot cull cows. Final body weight and nutrient digestibility were increased, and FCR was decreased. Adding up to 45% PKC in the diet of heifers kept on tropical pasture influenced neither carcass nor subcutaneous fat thickness. In buffaloes, supplementation with concentrated feed that included up to 90.62% PKC decreased milk yield but increased the amount of energy-corrected milk and milk fat content.

In contrast to beef cattle, incorporation of up to 30% PKC in the diets of fattening lambs reduced linearly feed intake, average daily weight gain, and digestibility. In lactating goats, using PKC as a feed supplement of up to 10% had no impact on nutrient digestibility and milk performance, but higher levels had a negative effect on milk yield, protein, fat, and total solids content. Contrary to cows, using PKC as a feedstuff for dairy goats decreased the expression of rumination and increased idling behavior. Moreover, PKC at 12% increased total weight gain, meat marbling, color, shear force, and loin eye area in feedlot kids.

In pigs, using up to 50% PKC on a dry matter basis as a substitute for maize can increase average daily feed intake and body weight gain (Adesehinwa, 2007) and decrease feed conversion ratio without affecting either performance (Adesehinwa, 2007) or back fat thickness. It may act as a replacement for maize in the diets of weaned pigs, up to 60%.

Utilization of PKC as a feedstuff for broilers has similar results as for pigs. Up to 10% incorporation into the diets of broilers does not affect FCR and carcass yield. Furthermore, 30% PKC resulted in ameliorated meat tenderness, juiciness, and flavor. In laying hens, using PKC in the ration did not affect egg performance, egg weight (Afolabi *et al.*, 2012; Chong, Zulkifli, and Blair, 2008), eggshell thickness (Afolabi *et al.*, 2012; Chong, Zulkifli, and Blair, 2008), or weight of albumin and yolk (Afolabi *et al.*, 2012). FCR was either not altered or decreased (Afolabi *et al.*, 2012; Chong, Zulkifli, and Blair, 2008). In Khaki Campbell ducks, adding up to 35% PKC in the diet ameliorated feed intake, egg production, and egg white mass, without affecting FCR and eggshell traits (Samsudin, Hendry, and KhTh, 2016).

22.2.7 Sugar beet pulp (SBP)

A total of 20% of the world's sugar production is based on sugar beet. The process of one ton of sugar beet yields 160 kg of sugar. Sugar beet pulp is a fibrous-based product, rich in neutral detergent soluble fiber, mostly pectin, that can be used as feedstuff for livestock, especially ruminants, used to replace starch-based concentrates. It is poor in sugar and has no structural carbohydrates but contains a high level of energy, fiber, phosphorus, and calcium. Many of these carbohydrates cannot be digested by humans; thus, using SBP as livestock feed can reduce feed-to-food competition in livestock.

As presented in Table 22.7, most studies regarding the incorporation of SBP into livestock diets have been conducted in ruminants, since it does not contain starch that can cause ruminal acidosis and it promotes the optimum pH conditions and general health in the rumen. Adding dried SBP up to 50% or 33% on a dry matter basis improved nutrient digestibility and rumen environment. SBP has been proposed as an alternative feedstuff to maize, wheat bran, and barley. Substitution of maize with up to 24% molassed SBP had no effect on milk yield, linearly improved the digestibility of fiber, and increased net profit. Replacement of yellow corn with dried SBP ameliorated milk yield and quality and decreased FCR. A total of 25% dried SBP instead of wheat bran in the diet of cows kept in organic systems observed an increase of dry matter intake and milk yield. Meanwhile, substituting barley or corn with up to 15% dried SBP resulted in reduction of starch intake and increase of rumen pH after feeding. Moreover, a study performed on Holstein calves showed that SBP incorporation in the rations can increase the length of meal and rumination periods and thus decrease the oral stereotypic behaviors of the calves

TABLE 22.6 Applications of palm kernel byproducts in animal diets.

Species	Level	Results	Reference
Pigs	50% or 100% to replace maize weight for weight	Decreased feed cost/kg live weight gain, performance and feed intake were not affected	(Adesehinwa, 2007)
Pigs	20–40%	FCR and daily weight gain were increased, eye muscle area and weights of joints and cuts were decreased	(Rhule, 1996)
Pigs	40 or 60% PKC (with or without enzyme supplementation) inclusion	No influence on carcass traits, meat quality, and acceptability	(Oluwafemi and Akpodiete, 2010)
Broilers	10–30%	Up to 10% no impact on carcass yield and feed intake	(García, Gernat, and Murillo, 1999)
Broilers	10-30%	Meat tenderness and juiciness not affected; flavor improved	(Okeudo *et al.*, 2005)
Laying hens	7.25–13.5%	Feed intake, FCR egg weight and productivity not influenced	(Rizal *et al.*, 2015)
Laying hens	5–15%	Egg productivity and blood parameters not affected, cost decreased	(Zanu *et al.*, 2012)
Laying hens	0.5, 1.48, 3.35, 5.22, 7.11, or 8.98%	FCR reduced, egg yolk index and yolk color increased, other egg traits not affected	(Afolabi *et al.*, 2012)
Laying hens	12.5–25%	Egg production and eggshell quality not affected, FCR decreased	(Chong, Zulkifli, and Blair, 2008)
Ducks	15–35%	Higher feed intake, no effect on egg production, increased egg weight, egg Haugh unit, shell thickness and yolk color not altered	(Samsudin, Hendry and KhTh, 2016)
Cows	8%, 16%, or 24% in total dry matter	Nutrient digestibility and feed intake best when 16%	(Santos *et al.*, 2019)
Dairy cows	25–75%	Milk production and chemical composition of milk and cheese not altered	(de Oliveira *et al.*, 2022)
Dairy cows	25–75%	Feed intake, crude protein, and non-fibrous carbohydrate digestibility increased	(Silva *et al.*, 2013)
Heifers	15–45% in the total dry matter	Rumination time increased, average daily weight gain of the heifers decreased, carcass weight and subcutaneous fat thickness not affected	(Soares *et al.*, 2024)
Lactating cows	5–15%	No effect on eating, ruminating, and idling time	(Pimentel *et al.*, 2015)
Goat kids	12–36% on dry matter basis	Improved total weight gain, meat marbling, lightness, and yellowness and increased loin eye area when 12%	(Rodrigues *et al.*, 2021)
Lambs	7.5–30.0% of dry matter	Decreased average daily gain of the animals and nutrient intake and digestibility	(Santos *et al.*, 2014)
Buffaloes	30.24%, 90.62% of dry matter	Increased fat-corrected milk production and fat and lactose value in milk but decreased daily milk production	(Galvão *et al.*, 2021)

TABLE 22.7 Applications of sugar beet byproducts in animal diets.

Species	Form	Level	Results	Reference
Cows	Mollased	120 g to 240 g/kg on a dry matter basis	Feed intake and milk yield were increased, fiber digestibility and rumen health were improved	(Münnich, Klevenhusen, and Zebeli, 2018)
Cows	Dried pulp	Replacement of 25–50% yellow corn	Improvements in digestion, rumen activity, milk yield, and chemical composition	(Mohsen *et al.*, 2021)
Cows	Pulp	10–30 g/kg dry matter	Increase in eating, ruminating and chewing time, improvement of rumen conditions and digestibility	(Mojtahedi and Danesh Mesgaran, 2011)
Cows	Pulp	Barley/corn + 5% or 15% SB	Feed intake, ruminal pH, and FCR were reduced, and digestibility was increased	(Nemati *et al.*, 2020)
Calves	Pulp	333–1000 g/kg as cracked maize replacement	Enhanced ruminal fermentation and nutrient digestibility and reduced FCR, while performance was not altered	(Abo-Zeid *et al.*, 2017)
Cows	Pulp	25% in the starter diet	Average daily gain, weight gain, and skeletal growth and rumination increased, stereotypic oral behaviors decreased	(Kargar *et al.*, 2021)
Sheep	Pulp	Replaced grass heavy up to 60%	Higher value level of lightness and linoleic acid, and a lower value of cooking loss, no effect on sensual meat traits	(Olfaz *et al.*, 2005)
Lambs	Pulp	12%	Ruminal environment improvement, prevention of ruminal acidosis, no effects on performance	(Bodas *et al.*, 2007a)
Lambs	Pulp	24%	Increase of shear force values and saturated fatty acids levels	(Bodas *et al.*, 2007b)
Goats	Untreated or treated with biological treatment	30% of the concentrated feed	Increase in body weight and feed intake, improvement of digestibility, rumen fermentations, milk yield, and kids' birth weight	(Aziz and Kholif, 2015)
Pigs	Molassed pulp	8% replacement of corn	Decrease in feed intake and number of lymphoid nodes in the colonic mucosa, increase in short-chain fatty acids in the distal colon	(Anguita *et al.*, 2007)
Pigs	Pulp	200 g/kg	Decrease in urinary nitrogen excretion and branched-chain fatty acids in the cecum of finisher pigs	(Lynch *et al.*, 2008)
Pigs	Pulp	3%	Reduction in the average daily gain but improvement of carcass quality, microbial profiles in pig feces and pork fatty acids profile were ameliorated. Sensory and acceptability increase	(Badaras *et al.*, 2022)
Weaned pigs	Pulp	0, 60, 120, 180, or 240 g SBP/kg	No impact on growth performance	(Wang, Beltranena, and Zijlstra, 2016)
Pigs	Pulp	23%	Enhanced gut health status, impairment of growth performance and carcass traits	(Laitat *et al.*, 2015)
Gestating sows	Pulp	119, 152, 185, and 217 g/kg	In early gestation, body weight and protein and fat retention increased with increasing fiber in the diets	(Wisbech, Bruun, and Theil, 2022)

Continued

TABLE 22.7 Applications of sugar beet byproducts in animal diets.—cont'd

Species	Form	Level	Results	Reference
Rabbits	Pulp	10, 20, or 30% of alfalfa hay	Neutral detergent fiber and crude protein digestibility were increased	(Carabaño *et al.*, 1997)
Broilers	Pulp	30 g/kg	Growth performance enhancement from 1 to 10 days of age and digestibility increase	(González-Alvarado *et al.*, 2010)
Broilers	Pulp	up to 50 g/kg	Improvement of feed conversion ratio, nutrient digestibility	(Jiménez-Moreno *et al.*, 2013a)
Broilers	Pulp	up to 50 g/kg	Development of the gastrointestinal tract	(Jiménez-Moreno *et al.*, 2013b)
Broilers	Pulp	23, 46, or 92 g/kg	Reduced total serum cholesterol concentrations and digestibility of organic matter	(Pettersson and Razdan, 1993)
Broilers	Pulp	2.50%	Improvement of body weight, FCR, and giblet relative weight	(Kumari *et al.*, 2014)
Broilers	Pulp	7.50%	Decrease in body weight, weight gain, low-density lipoprotein, and total cholesterol	(Abdel-Hafeez *et al.*, 2018)
Broilers	Pulp	7.50%	Decrease in villus height and villus height to crypt depth ratio	(Abdel-Daim *et al.*, 2020)
Laying hens	Pulp	3–7%	Increase in egg production, decrease in FCR, Haugh unit, yolk color, egg yolk cholesterol	(Selim and Hussein, 2020)

and improve their emotional state. In buffaloes, as in cows, maize substitution with dried SBP improved feed digestibility and decreased FCR (Abo-Zeid *et al.*, 2017).

In fattening lambs, using SBP as a feedstuff at 12% ameliorated rumen conditions but did not alter growth performance. Replacing 60% grass hay with dried SBP in the rations of rams reduced meat cooking loss but did not affect the quality of the meat or its sensual attributes. Still, replacing barley with SBP in the nutrition of fattening lambs caused an increase in shear force value and PUFAs level in the meat. Aziz and Kholif (2015) report that utilization of SBP in goats during pregnancy and early lactation stage can promote performance and be beneficial both for the mother and the goat kids, by increasing their weight upon birth.

In gestating sows, using up to 21.7% as a feedstuff resulted in increased feed intake and body weight gain in the early and mid-gestation stage. Although SBP is rich in fiber, due to its increased metabolized energy and N efficiency, the animals retained more protein and less fat. Incorporating SBP in the diet of growing pigs reduced feed intake (Anguita *et al.*, 2007) and average daily gain (Badaras *et al.*, 2022) in contrast to sows. Nonetheless, carcass quality and sensory traits were improved. Moreover, gut microbiota health was enhanced and gastric lesion score was decreased upon the use of 23% SBP in the diet.

SPB has also been studied as an alternative feedstuff for rabbits. Substitution of alfalfa hay with SBP up to 30% had no effect on growth performance but increased the digestibility of crude protein (Carabaño *et al.*, 1997). Also, providing concentrate based on barley and SBP to fattening rabbits did not alter the characteristics of the meat.

Application of SBP as a feedstuff for broilers increased growth performance and decreased FCR when used up to 5%. Gastrointestinal tract weight also increased. Using 7.5% SBP on a dry matter basis in rations reduced growth performance, villus height, and villus height to crypt depth ratio (Abdel-Daim *et al.*, 2020) but also decreased the serum total cholesterol and low-density lipoprotein levels. Higher levels of SBP in the rations had the same effect on cholesterol but impaired nutrient digestibility.

22.2.8 Tomato pomace

Tomato (*Solanum lycopersicum*) cultivation in 2021 reached 189 million tons. The main byproduct of the tomato canning industry is tomato pomace (TP). The average annual volume of TP is around 4 million tons only in Europe. TP represents approximately 4% of the initial tomato weight and consists mostly of peel, seeds, and juice leftovers. It is rich in fiber, sugar, and protein. It contains pectin (7.55%) and minerals (3.92% on a dry matter basis). Moreover, TP is rich in various bioactive compounds, with lycopene being the most important one with significant antioxidant properties. Table 22.8 summarizes the studies of TP use in farm animal rations.

In dairy cattle, inclusion of 10% ensiled TP on a dry matter basis as a replacement for maize silage did not affect milk yield but increased the content of vitamins in the diet and improved the antioxidant status of the animals and their immune system before parturition. Ensiled mixture of TP with apple pomace in the diet of Holstein cows reduced chewing activity and ameliorated rumen conditions by increasing pH and increasing total volatile fatty acids. On the contrary, using up to 11.2% dried TP in the rations of beef cattle reduced voluntary feed intake and growth, due to reduction of the synthesis of bacterial protein in the rumen.

In lactating Saanen goats, adding 40% dried TP in the diets increased milk yield (approximately 28%) and fat content. Nonetheless, using 60% TP in the rations had the opposite effect. Incorporating 10% dried TP resulted in increased fat and PUFA levels in the milk, but milk yield was not altered. Hence, using TP as a feedstuff for goats can improve the quality of the milk and even increase productivity. As in beef cattle, incorporation of dried TP in the diets of fattening lambs reduced feed intake and increased PUFA levels in meat. Replacing soybean with dried TP up to 20% in the diet of fattening lambs has no effect on growth performance, but meat quality was not investigated. Studies on adding lycopene to the rations of lambs resulted in an increase of PUFAs content, a decrease of lipid peroxidation, and a darker and redder meat color.

Similar positive results have been reported for pigs. Incorporation of up to 5% TP as a feed supplement in the diet improved meat tenderness (Chung *et al.*, 2014) and enhanced meat oxidation stability and α-tocopherol content. In another study, Aguilera-Soto *et al.* (2014) added up to 30% ensiled TP in the liquid diets of finishing pigs and detected no alteration of carcass traits.

In broilers, incorporation of up to 20% dried TP in the rations had no impact on either growth performance or feed intake. Nonetheless, TP increased meat water holding capacity and drip loss. TP waste can also be used as a valuable natural antioxidant in broilers' diet. Dried TP at 7 to 10% was used as a feedstuff for broilers under heat stress. The negative effects of stress were alleviated, the level of antioxidant enzymes was increased, and the immune response of the birds was strengthened. Enzyme-fermented TP can enhance the antioxidant properties of TP and serve as an alternative solution instead of using synthetic antioxidants in diets. Not only TP but also lycopene can be used as an antioxidant in the

TABLE 22.8 Applications of tomato byproducts in animal diets.

Species	Form	Level	Results	Reference
Pigs	Dried	3 and 5%	Improvement of meat tenderness	(Chung *et al.*, 2014)
Pigs	Silage	Up to 30% DM	Increase of growth performance, no effect on carcass characteristics	(Aguilera-Soto *et al.*, 2014)
Quails	Dried	5 and 10%	Increase in PUFAs and unsaturated/saturated fatty acid ratio, enhancement of meat oxidative stability	(Botsoglou *et al.*, 2004)
Quails	Dried	2.5–5%	Malondialdehyde levels in serum, liver, and muscle were decreased	(Sahin *et al.*, 2008)
Ducklings	Dried	0, 10, 15, 20% on dry matter	Increase of body weight, total cholesterol, triglycerides, high-density lipoprotein, cost per kg live weight were decreased	(Omar *et al.*, 2019)
Sheep	Dried	10%	Increased fat and PUFAs content of milk	(Romano *et al.*, 2010)
Lambs	Lycopene	0.05, 0.1, or 0.2 g/kg	Darker and redder meat while muscle fat content and lipid oxidation values were decreased	(H. Jiang *et al.*, 2015)
Lambs	Lycopene	0.2 g/kg	Improvement of antioxidant status of the lamb, optimization of lipid profile, decrease of total cholesterol, total triglycerides, and low-density lipoprotein cholesterol	(Hongqin Jiang *et al.*, 2015)
Lambs	Dried	*ad libitum*	Reduced feed intake, no effect on performance, increased PUFAs, linoleic acid, γ-tocopherol and retinol in meat, no effect on oxidation	(Valenti *et al.*, 2019)
Goats	Dried	0%, 20%, 40%, and 60%	Decrease in body weight, higher milk production, improved the milk quality	(Mizael *et al.*, 2020)
Dairy cows	Ensiled	10% replacement of crop maize	Milk yield and composition were not affected, concentration of vitamins in milk significantly increased, improvement of antioxidant status and increased immunoglobulins	(Tuoxunjiang *et al.*, 2020)
Beef cattle	Dried	3.2, 8.0, and 11.2% replacement of soybean	FCR, blood urea concentrations were increased, bacterial protein synthesis was reduced	(Yuangklang *et al.*, 2010)
Dairy cows	Ensiled	Mixed with apple pomace, use of mixture 15–30%	Reduction of chewing activity, higher concentration of volatile fatty acids in rumen and lower rumen pH	(Abdollahzadeh *et al.*, 2010)
Laying hens	Dried	Up to 10%	No effect on daily feed intake, growth performance, egg weight, egg quality traits	(Jafari, Pirmohammadi, and Bampidis, 2006)
Laying hens	Dried	Up to 10%	No effect on growth performance, egg weight, eggshell weight and thickness, Haugh units and yolk color, serum and yolk cholesterol levels	(Nobakht and Safamehr, 2007)
Laying hens	Dried	Up to 190 g/kg	Increase in yolk score, no effect on FCR, egg production	(Salajegheh *et al.*, 2012)

Laying hens	Dried	5 or 10 g /kg	Linear increase in egg production, egg weight, and yolk color, serum and egg yolk lycopene, β-carotenoids and vitamin A content in egg yolk were increased	(Akdemir *et al.*, 2012)
Laying hens	Dried	0.02, 0.04, or 0.08 g/kg	Improvement of fertilization and antioxidant capacity	(Sun *et al.*, 2014)
Broilers	Dried	0.7 g/kg − up to 10&	Amelioration of the negative effects of heat stress on oxidative status, immune response, and bone composition, without affecting growth	(Hosseini-Vashan, Golian, and Yaghobfar, 2016)
Broilers	Fermented	0.25 g/kg synthetic antioxidant, 10 g/kg TP or 10 g/kg fermented TP	Antioxidant capacity, growth boosting	(Gungor, Altop, and Erener, 2024)
Broilers	Dried	0, 4, or 6%	No effect on water holding capacity or drip loss	(Mohammed *et al.*, 2021)
Broilers	Dried	5, 10, 15, and 20%	Economic efficiency, no effect on chicks' growth	(Yitbarek, 2013)
Broilers	Dried	5, 10, 15, and 20%	No impact on growth of broiler chicken at 29 to 42 days	(Lira *et al.*, 2010)

nutrition of both broilers and laying hens, as indicated with detail in Table 22.8. Utilization of TP as a feedstuff for laying hens does not affect productivity or egg traits. Nonetheless, it can be a tool to increase profit by reducing feed costs. Utilization of TP increased egg productivity and improved egg quality in both laying hens (Akdemir *et al.*, 2012) and quails. Botsoglou *et al.* (2004) reported increased meat antioxidant capacity and increased level of PUFAs in quails fed with 5 to 10% TP. Finally, 20% dried TP in the diet of Mallard ducklings was found to increase body weight gain, while FCR, cholesterol, and total triglycerides levels were decreased.

22.2.9 Others

In tropical and subtropical areas, the transfer and import cost of various feedstuffs, especially cereals, is high, while cultivation of feedstuffs with high fat and protein content is limited. Furthermore, forage can be significantly limited due to rain and heavy weather conditions. These reasons induce a lack of feed and a significant economic burden for farmers. Thus, valorizing AIBPs in livestock nutrition can contribute to minimizing the above difficulties. Fruits are abundant, so their byproducts are an alternative and valuable source of energy and fiber for livestock nutrition. As indicated in Table 22.9, banana, papaya, mango, pineapple, melon, and watermelon can be incorporated into the diets of livestock, mainly ruminants and broilers, without altering performance and simultaneously reducing FCR and improving the quality of animal-derived products. Moreover, some fruit species are rich in functional ingredients with antibacterial and anti-anthelmic factors.

In addition to tropical fruit waste, Table 22.9 also summarizes studies on the use of broccoli and carrot byproducts in livestock diets. As indicated, broccoli residues are promising, especially for ruminants, since they improve milk and meat quality, and carrot leaves for laying hens since they increase egg production and fortify eggs with bioactive compounds (Bidura *et al.*, 2021).

22.3 Potential limitations of utilizing agro-industrial byproducts in animal nutrition and future perspectives

Although research on exploiting AIBPs as animal feed is flourishing, they are still underutilized due to various limitations. Their availability is seasonal since the cultivation and processing in agro-industry is also seasonal. This is an obstacle especially for vegetables and fruits that are used raw or dried in livestock diets and not often ensiled (Georganas *et al.*, 2023). Furthermore, there is variation not only in quantity but also in quality. Chemical composition, and thus nutritional value and digestibility, can vary significantly depending on season, climate, origin (Alnaimy, 2017), or processing (Georganas *et al.*, 2023). Thus, AIBPs cannot be added to the rations as a feedstuff of standard nutritive value.

Another limitation is that they may contain antinutritional factors or even toxins. Apple pomace may contain pesticides, polychlorinated biphenyls have been detected in citrus pulp (Alnaimy, 2017), and sugar beet pulp contains saponins. Sugar beet pulp and grapes may also contain a high level of heavy metals. Pathogenic microorganisms and their toxins are another hazard. Many AIBPs, mostly byproducts of the fruit juicing industry, have a high moisture content that may induce sensitivity to growth of yeast and bacteria and, consequently, spoilage. Mycotoxin growth is also a problem. Drying of liquid byproducts reduces this danger and prolongs shelf-life, as does ensiling. Especially sun drying can be a simple and low-cost method, but it requires space. However, dehydration may result in protein reduction. Another advantage of drying is that it reduces the transportation cost compared to bulk byproducts. An alternative to direct drying of bulk byproducts could be mixing with other solid byproducts prior to drying to reduce the drying period. Ensiling is the most promising solution due to various advantages. It reduces the moisture content without causing nutrient degradation in contrast to dehydration and is a low-cost and easy-to-apply process to almost all AIBPs.

Thus, in many cases, there is need for preparation, preservation, and improvement of the nutrient content of AIBPs before their incorporation into the rations, like removal of hazardous microorganisms and addition of substances that block the action of antinutritional factors or increase the digestibility and bioavailability of nutrients (Ajila *et al.*, 2012). Nonetheless, this raises the cost of AIBPs as feedstuffs and requires equipment, time, energy, and technical knowledge, and AIBPs are considered waste and their total cost as feedstuff can result in surpassing by far their discard cost as waste. Due to this, it is important to increase their value as a feedstuff with as many economic alternatives as possible. At the same time, there is a need to highlight and promote all the advantages of using AIBPs as an alternative feed and their sustainable profile. Economic studies are needed to persuade for the economic profit of the circular economy, and marketing, to promote use by middle and small farmers, since farmers do not always realize the nutritive value of AIBPs (Ajila *et al.*, 2012); meanwhile, economical and low-cost ways of preparation and quality improvement can support their utilization.

Solid-state fermentation is a processing method that can enhance or transform the nutritional content of AIBPs and decrease the content of antinutritional factors, resulting in more effective and efficient digestibility. Especially protein loss

TABLE 22.9 Applications of several byproducts in animal diets.

Species	Processed food	Byproduct	Level	Results	Reference
Sheep	Banana (*Musa* spp.)	Rejected green fruits	1.5–3 kg/day	Digestibility was not affected by high fiber concentration	(Archimède *et al.*, 2010)
Lambs	Banana (*Musa* spp.)	Leaves, pseudo-steams	70–80% DM	No impact on growth performance, carcass yield	(Marie-Magdeleine *et al.*, 2009)
Lambs	Banana (*Musa* spp.)	Foliage	7 kg/animal/day	Reduction of feed intake, growth, fecal worm egg counts	(Marie-Magdeleine *et al.*, 2010)
Sheep/ Cows	Banana (*Musa* spp.)	Leaf hay, pseudo-stem	50–100% DM	Improved rumen conditions	(de Oliveira *et al.*, 2022)
Cows	Banana (*Musa* spp.)	Rejected green fruits	15 kg/animal/day	Increased liveweight gain	(Ibrahim *et al.*, 2000)
Bulls	Banana (*Musa* spp.)	Rejected fruits	25–100% DM	Increased feed intake and growth	(Sukri, Zahari, and Awis, 1999)
Growing calves	Banana (*Musa* spp.)	Dried stems	10–40%	Daily weight gain not affected up to 10%	(Sen *et al.*, 2014)
Goats	Banana (*Musa* spp.)	Pelleted stems	100% DM	Growth, rumen pH, and volatile fatty acids were improved	(Aswandi, 2016)
Goats	Banana (*Musa* spp.)	Unripe fruits, leaves	4 kg/animal/day	Voluntary intake and nutrient digestibility were increased	(Pieltain *et al.*, 1998)
Buffaloes	Banana (*Musa* spp.)	Ensiled green waste	Up to 15% of total diet	Higher milk yield, lower content in protein, fat, and solids	(Khattab *et al.*, 2000)
Pigs	Banana (*Musa* spp.)	Stems (fresh or fermented)	Metabolic cages trials	Enhanced intestinal morphology, mainly villi height, no effect on FCR	(Arjin *et al.*, 2020)
Pigs	Banana (*Musa* spp.)	Stalks, pseudo-stalks (fermented)	10% DM	Low nutrient digestibility	(Ly, Garcia, and Dominguez, 1997)
Pigs	Banana (*Musa* spp.)	Stems (fermented)	40–70% DM	Increased intestinal weight, no effect on performance and carcass traits	(Huy *et al.*, 2021)
Rabbits	Banana (*Musa* spp.)	Leaves	Up to 40% DM	No effect on performance	(Rohilla and Bujarbaruah, 2000)
Broilers	Banana (*Musa* spp.)	Peels	10–30% DM	Daily weight was increased, FCR was decreased	Abel et al., 2015
Broilers	Banana (*Musa* spp.)	Peels	1.5–3%	Ameliorated growth, dressing, FCR	(Siyal *et al.*, 2016)
Goats	Watermelon (*Citrullus vulgaris*)	Husk	30%	Increased DM, dry protein digestibility	(Sanwo *et al.*, 2021)
Broilers	Watermelon (*Citrullus vulgaris*)	Husk (alkaline treated)	10–20% maize replacement	Liver was negatively affected, FCR was improved	(Akinbami *et al.*, 2021)

Continued

TABLE 22.9 Applications of several byproducts in animal diets.—cont'd

Species	Processed food	Byproduct	Level	Results	Reference
Broilers	Watermelon (*Citrullus vulgaris*)	Seed (defatted, fermented)	100% protein source	Increased protein digestibility, removal of antinutritional factors	(Oloyede, Otunola, and Apata, 2003)
Cows	Watermelon (*Citrullus lanatus*)	Vine (fermented)	25–100% hay replacement	Increased milk yield and decreased FCR with 25%	(Soliman *et al.*, 2020)
Lambs	Watermelon (*Citrullus lanatus*)	Seed cake	25–100% DM	Fat content was reduced, digestibility was not affected	(Beshir and Babiker, 2009)
Broilers	Watermelon (*Citrullus lanatus*)	Rind	25–100% wheat offal	No impact on performance and digestibility up to 25%	(Otu *et al.*, 2021)
Pigs	Watermelon (*Citrullus lanatus*)	Waste	20–40% DM	No effect on growth and digestibility at 20%	(Adebiyi *et al.*, 2020)
Goats	Watermelon (*Citrullus lanatus*)	Vine (fermented, dried)	25–50%	Improved milk yield, fat, protein content	(Hassan *et al.*, 2019)
Sheep	Papaya (*Carica papaya*)	Leaves	4–8% (multinutrient blocks)	Palatability and feed intake were increased	(Pujaningsih *et al.*, 2022)
Rabbits	Papaya (*Carica papaya*)	Seed powder	4–8% DM	Highest carcass yield at 6%	(Konmy *et al.*, 2024)
Rabbits	Papaya (*Carica papaya*)	Leaves	15–45% DM	Increased weight gain and carcass yield	(Jiwuba, 2018)
Broilers	Papaya (*Carica papaya*)	Leaves	5–15%	Weight gain and FCR were not altered	(Unigwe *et al.*, 2014)
Broilers	Papaya (*Carica papaya*)	Seed powder	0.5–1%	Meat antioxidant capacity was enhanced, performance was not affected	(Muazu and Aliyu-Paiko, 2020)
Laying hens	Papaya (*Carica papaya*)	Peels	3–12%	Egg yolk weight, color, and cholesterol were increased	(Leke *et al.*, 2019)
Quails	Papaya (*Carica papaya*)	Leaves	5–15%	Increased body weight at 5%	(Ampode, 2019)
Quails	Papaya (*Carica papaya*)	Leaves	2–6%	Improved growth performance, FCR, and digestibility	(Kanyinji, Zulu, and Chionile, 2014)
Sheep	Mango (*Mangifera indica*)	Peels, seed kernels	Ad libitum	No impact on performance, protozoa reduction in feces	(Sanon and Kanwe, 2010)
Sheep	Mango (*Mangifera indica*)	Seed kernels	11.25–22.5% DM	Digestibility was increased	(Omer *et al.*, 2019)
Sheep	Mango (*Mangifera indica*)	Rejected fruits	12.5–37.5% DM	FCR, water intake were linearly increased	(Ibrahim *et al.*, 2020)
Cows	Mango (*Mangifera indica*)	Peels (silaged)	*Ad libitum*	Growth was improved, blood urea and nitrogen were decreased	(Aung *et al.*, 2024)

Broilers	Mango (*Mangifera indica*)	Fruit rejects	5–20%	10–15% no impact on performance	(Orayaga, 2015)
Broilers	Mango (*Mangifera indica*)	Seed kernels (boiled)	40–80%	Performance was not altered when up to 40%	(Admasu, Wondifraw, and Gash, 2020)
Laying hens	Mango (*Mangifera indica*)	Seed kernels	50–250 g/kg maize	Reduced eggshell thickness	(Odunsi, 2005)
Cows	Pineapple (*Ananas comosus*)	Waste (silage)	25%	Body weight gain and nutrient intake were increased	(Kyawt *et al.*, 2020)
Cows	Pineapple (*Ananas comosus*)	Stem (silage)	Ad libitum	Meat quality was not affected, ribeye area was increased	(Hattakum *et al.*, 2019)
Cows	Pineapple (*Ananas comosus*)	Waste	5.33% DM	Milk yield was increased, quality was not affected	(Raseel *et al.*, 2020)
Buffaloes	Pineapple (*Ananas comosus*)	Waste (silage)	20–80%	Best digestibility and blood parameters when 60%	(Jetana *et al.*, 2009)
Pigs	Pineapple (*Ananas comosus*)	Waste	90–270 g/kg feed	Backfat thickness was decreased, lean meat area was increased	(Silvestre Vasconcelos *et al.*, 2020)
Rabbits	Pineapple (*Ananas comosus*)	Peels	20–40%	FCR and weight gain were improved	(Aboh *et al.*, 2013)
Broilers	Pineapple (*Ananas comosus*)	Leaf powder	1–3%	Improved growth, intestinal microbiota	(Rahman and Yang, 2018)
Laying hens	Pineapple (*Ananas comosus*)	Peels (fermented)	5–20%	Egg cholesterol reduction, performance was not affected	(Adrizal *et al.*, 2021)
Pigs	Carrot (*Daucus carota*)	Byproducts (fermented)	3–9%	Enhanced hepatic function, immune system	(Chu and Park, 2023)
Rabbits	Carrot (*Daucus carota*)	Leaves	15–60%	Best performance when 15%	(Abdu *et al.*, 2012)
Rabbits	Carrot (*Daucus carota*)	Leaves	10–40%	No effect on carcass yield, blood parameters	(Ngoshe, Igwebuike, and Adamu, 2013)
Laying hens	Carrot (*Daucus carota*)	Leaves	0.35–0.45%	Increased yolk color, xanthophyll content	(Titcomb *et al.*, 2019)
Laying hens	Carrot (*Daucus carota*)	Leaves (fermented)	2–6%	Increased production, yolk color, β-carotene content	(Bidura *et al.*, 2021)
Cows	Broccoli (*Brassica oleracea*)	Waste (pelleted)	0.2–0.8% DM	Higher milk fat content, milk yield was not altered	(Yi *et al.*, 2015)
Sheep	Broccoli (*Brassica oleracea*)	Waste (silage)	10–20% DM	No impact on blood parameters, growth	(Partovi *et al.*, 2020)
Sheep	Broccoli (*Brassica oleracea*)	Waste	20–40%	Increased growth, decreased cholesterol	(Mahmoud, 2016)
Pigs	Broccoli (*Brassica oleracea*)	Stem, leaves	5–10%	Meat color improvement, performance was not affected	(Sun *et al.*, 2023)
Laying hens	Broccoli (*Brassica oleracea*)	Waste	4–12%	Egg weight, egg yolk color, α-tocopherol content were increased	(Mustafa and Baurhoo, 2018)

in fruit pomaces and lipid rancidity in olive cake (Chebaibi *et al.*, 2019) are minimized by solid-state fermentation compared to traditional methods like drying, ensiling, or composting. Although the cost compared to traditional methods is high, the advantages of nutrient value are significant. Moreover, it is more environmentally sustainable and effective in lowering antinutritional factors. Another alternative is ensiling AIBPs. Although not as effective as solid-state fermentation, it contributes to eliminating or blocking antinutritional factors, and it is lower in cost and easier to apply.

Nevertheless, food safety is of major importance, and a circular economy may pose safety risks in the food supply chain if not properly employed. Although there are numerous studies on the reuse of AIBPs, the safety of some sensitive to deterioration AIBPs in a circular economy scheme is under-researched. Researchers have addressed the significance of safety in a circular economy for other feed (e.g., former food items, catering trash, and seaweed). Although the EU promotes a circular economy, more procedures that ensure the safety of AIBPs are expected to be developed. While there have been instances of feed contamination, such as dioxins from byproducts, there is a lack of information on the risks associated with AIBPs and their potential spread throughout the food supply chain. This is an obstacle to incorporating agro-industrial waste in livestock diets and needs to be researched further.

22.4 Conclusions

AIBPs can be added as valuable feed to animals' diet, instead of being considered waste and a threat for the environment. Incorporating them into livestock rations can enhance both animal health and the quality of the final products and maximize farmers' returns. In some cases, even performance is increased. Moreover, AIBPs are rich in bioactive compounds and functional ingredients, mainly polyphenols, that can beneficially improve the quality of the final products. Various AIBPs are being studied as an alternative feedstuff, mainly fruit and vegetable waste, but also byproducts of oil extraction, like olive and palm kernel cake, with positive effects on animals' nutrition and the quality of the derived products. Although there are still limitations in the use of these byproducts in livestock nutrition, it can be argued that they have potential as alternative, nutritional, and low-cost feedstuffs. Despite requiring preparation in most cases for improving their nutritional value and safety before their use in livestock rations, economic and relatively simple solutions like sun-drying and ensiling can be an option in many cases, especially for fruits and vegetables. Removal of antinutritional factors and treatment via solid-state fermentation are promising methods for future research.

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Chapter 23

Biochar production: Utilizing waste for carbon sequestration and soil improvement

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Chapter Outline

23.1. Introduction **415**
23.2. Biochar production from waste 416
23.3. Biochar properties 418
23.4. Biochar induced carbon sequestration 420
23.5. Biochar-induced soil improvement 421
23.6. Conclusion 425
References **426**

23.1 Introduction

"Biochar" represents black carbon derived from biomass pyrolysis in oxygen-free or oxygen-limited environments, so biomass is not subject to complete combustion. Biochar is a stable carbon (C) compound created when biomass (feedstock) is heated to high temperatures (300 and 1000°C) under limited (preferably zero) oxygen concentrations. Biochar is a relatively new term; however, it is not a new substance. Biochar deposited in soil through natural events, such as forest and grassland fires, has been reported worldwide. Biochar has been reported to be present in different parts of the world since ancient times. In fact, natural deposits of biochar in areas like the North American Prairie are some of the most fertile soils in the world (Singh *et al.*, 2014). There is evidence of the use of biochar from 2,000 years ago. The concept of *Terra preta,* which is also known as Amazonian dark earth, was found to be mentioned in the literature (Glaser *et al.*, 2015). Parts of Asia, especially Japan and Korea, have a long history of biochar application in agriculture. Recently, growing interest toward sustainable farming systems, such as Korean natural farming, has rejuvenated biochar application in Western agriculture.

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Biochar applications have drawn much attention in the last two decades because they are vital in improving soil quality and sustainable crop production (Khatun *et al.*, 2021). The biochar concept aims to abate the enhanced greenhouse effect by sequestering C in soils while improving soil quality. More recalcitrant carbon present in biochar imparts more C sequestration potential of biochar than any other organic material. The estimated residence time of biochar-carbon is hundreds to thousands of years, while the residence time of carbon in plant material is decades. The carbon storage potential of biochar is widely hypothesized, although it is still largely unquantified (Saha, Basak, and Banerjee, 2022). Concomitant with carbon sequestration, biochar is intended to improve soil properties and soil functioning relevant to agronomic and environmental performance. Considering biochar's multidimensional and cross-cutting nature, an imminent need is anticipated for a robust and balanced scientific review to effectively inform policy development on the current state of knowledge regarding biochar application to soils. Therefore, in this chapter, effort has been made to synthesize information about waste biomass-derived biochar on carbon sequestration potential and improvement in soil properties.

23.2 Biochar production from waste

Several waste materials or feedstock can be efficiently converted to biochar. The term feedstock or biomass plays an important role in the production of biochar. The quality of biochar largely depends on the nature and quality of the feedstock. The biomass is mainly of lignocellulosic and non-lignocellulosic types. Lignocellulosic biomasses are the most prominent bio-resources, including agricultural, wood, furniture, and municipal solid waste. Non-lignocellulosic materials include animal waste, sewage sludge, and algal biomass (Krishnan *et al.*, 2021). Non-lignocellulosic materials harm the biological system due to heavy metals and other materials containing nitrogen, sulfur, and phosphorus in higher concentrations than lignocellulosic biomass (Senthil and Lee, 2021). Cellulose, hemicellulose, and lignin are strongly bonded with each other by different chemical forces that deform the rigid structure of the biomass. This complex cellular network forms the porous structure of the biochar once converted, and the properties of the biochar are also determined. A range of conversion techniques can convert biomass to biochar effectively. Thermal techniques are the most commonly used method employed for producing biochar. However, biological treatments are also available for bioconversion, such as hydrolysis, anaerobic digestion, fermentation, etc. Thermal treatments, such as pyrolysis, gasification, torrefaction, and hydrothermal carbonization, are mostly applied for biochar production.

The pyrolysis process is defined by biomass's thermochemical conversion at varying temperatures between 300 and 900°C without or in the presence of limited oxygen (Yaashikaa *et al.*, 2020). To maintain a carbon content of >95%, the applied temperature should be above 700°C. Although it is feasible for woody biomass, it becomes ash agricultural residues (non-woody type) treated at high temperatures. That is why the handling temperature is below 700°C (Nadarajah, Asharp, and Jeganathan, 2024). Any lignocellulosic biomass's initial moisture content determines the biochar's ultimate characteristic. <30% moisture content is often acceptable, although up to 10% is considered optimum (Suliman *et al.*, 2016). Since pyrolysis produces a wide range of byproducts, selecting the right procedure is critical for producing high-quality products. The kind of pyrolysis also determines the particle size of the biochar product. Depending on the heating rate, residence time, and reaction temperature, the process can be divided into three categories: fast, intermediate, and slow pyrolysis. Fast pyrolysis involves extreme temperature with short residence time (0.5−2 s) and rapid heating rates (10−1000°C/s) (Tomczyk, Sokołowska, and Boguta, 2020). As the residence time is very low and the heating rate is high, secondary reactions are avoided, which maximizes output. Due to the avoidance of secondary reactions, the pyrolysis process is endothermic. Biomass containing <10% moisture is recommended for undergoing this process. Fast pyrolysis is recommended. Additionally, the low moisture level in feedstock enables it to get ground into fine particles that allow quick heating as well as conversion into biochar (Lee, Lu, and Chang, 2020). For intermediate pyrolysis, the reaction is slower than for fast but quicker than for slow. It operates at 450 to 550°C, with a residence time of 10 to 30 s, and produces relatively higher charcoal than fast pyrolysis (Ge *et al.*, 2021). This intermediate pyrolysis prevents the production of high molecular weight tars that produce a range of products (biochar, bio-oil, and gases). Contrary to fast pyrolysis, the shape and size of biomass (pellets and chips to bigger particles) are less critical for end-product quality (Mbarki *et al.*, 2019). Another technique, i.e., slow pyrolysis, is adhered with moderate to low operation temperature (300−550°C), with prolonged residence time (5−30 min, up to 25−35 h) and slow heating rates (0.1−0.8°C/s) (El-Naggar *et al.*, 2019). This process maximizes biochar yields by maintaining secondary reactions accomplished by higher residence periods. Moderate heating with a slow heating rate favors biochar production. Biomass rich in minerals yields less biochar in this process. Due to the systematic development of secondary reactions, the pyrolysis process is exothermic. Feedstock with varying particle sizes (5−50 mm) can be suitable for slow pyrolysis (Sakhiya, Anand, and Kaushal, 2020). Another approach, flash pyrolysis, involves very brief residence time (<0.5 s) with high heating rates (>1,000°C/s) and operation temperature of

800 to 1,000°C (Gaurav *et al.*, 2020) that is optimized to produce bio-oil. This process produces products identical to fast pyrolysis. Feedstock with tiny particle sizes (<0.2 mm) is needed for flash pyrolysis. In addition to these methods, microwave-assisted pyrolysis is a relatively recent strategy for effectively converting waste biomass into energy (Ge *et al.*, 2021). Rather than the transfer of heat, this process involves the transfer of energy. Heat energy is derived from electromagnetic energy, which is released within biomass rather than any external source (Liu *et al.*, 2018). Unlike the conventional method, the temperature remains higher at the biomass's center than at the surface. In this process, the electromagnetic waves interact with the dipoles of feed molecules during heat circulation, which facilitates uniform and controlled heating. The physicochemical properties of biochar produced by microwave pyrolysis are unique and very stable compared to traditional pyrolysis. This process poses several advantages over traditional pyrolysis, including selective and uniform heating with a faster heating rate and heat transfer profile. For that, thermal transformation happens effectively and quickly, increasing product quality. Other advantages include high heating efficiency facilitated by in situ heating and less production of hazardous materials and pollutants, making this approach environmentally sound (Venkatesh *et al.*, 2022). However, one major drawback of microwave heating is its operation cost, associated with consuming large quantities of electricity.

Another thermal treatment, i.e., gasification, is entirely different from pyrolysis due to its high reaction temperature. This process involves the partial decomposition of biomass at a short residence time of 10 to 20 s with a high operation temperature (600−1,200°C) (Tomczyk, Sokołowska, and Boguta, 2020). The end product composition is governed by residence time, reaction temperature, particle size, and gas composition. Technically, this process yields no biochar since most of the biomass gets transformed into gas and ash in the course of this process. However, depending on conditions followed during the process, it can provide <10% of biochar yield. The primary gasification product, fuel, can produce heat (Nadarajah, Asharp, and Jeganathan, 2024). The torrefaction process is considered the beginning of pyrolysis. It occurs at 250 to 280°C with low heating rates. It produces black or brown products having less mechanical strength. This process aids in decreasing biomass weight, increases its energy density, improves hydrophobicity, and minimizes transportation, promoting commercial utilization of wood. Torrefaction is a critical pre-processing step for improving feedstock's physiochemical characteristics, yielding good-quality biochar. Hence, this process has gained significant interest in bioenergy. However, the production of torrefaction cannot be considered biochar (property lies between biomass and biochar) since some fraction of the biomass remains in an end product unsuitable for energy requirements. Hydrothermal carbonization (HTC) is another technique associated with high pressure and temperature that produces char−water−slurry in the presence of compressed, hot water. This process is called wet torrefaction, as it is accompanied by a low reaction temperature (temperature: 180−260°C, pressure: 2−5 MPa) and the presence of water. Apart from producing gaseous and liquid fuel, important chemicals are derived during HTC, and that is why this process is gaining attention day by day from the energy sector. HTC is accomplished at lower temperatures (180−260°C) while hydrothermal vaporization (HTV) and hydrothermal liquefaction (HTL) occur above 260. HTV and HTL are to produce gaseous and liquid fuel, not to produce biochar from waste material. The process of HTC has benefits over traditional pyrolysis, such as no additional attempt is required to reduce the initial moisture content present in biomass (as it is accomplished in the presence of water), which makes this process economically sound. Factors like operation temperature, feedstock moisture content, processing configurations, and vessel arrangements strongly influence the nature of the product (solid, liquid, or gas). The solid end product is known as "hydrochar," with a recovery of ∼40 to 70%. Due to high moisture content, the degradation of hydrochar is less energy-intensive than biochar. This moisture-holding capacity is associated with many oxygen-containing functional groups and high aromaticity. Hydrochar is of good quality and has production merit in terms of economical pathways and definitive mechanical configurations compared to biochar. Figure 23.1 illustrates different approaches to the thermal conversion of waste biomass into biochar.

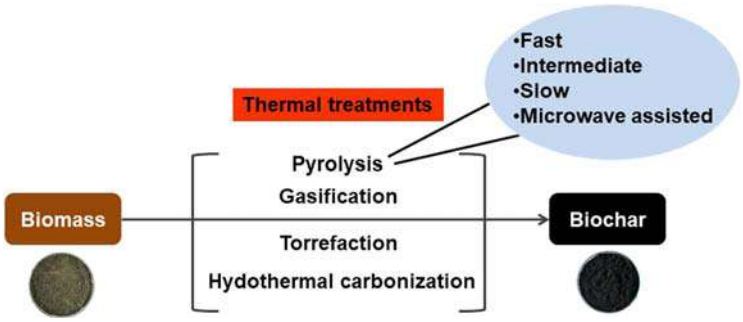


FIGURE 23.1 The thermal conversion process of biomass-producing biochar. *Adapted from Nadarajah, Asharp, and Jeganathan (2024).*

23.3 Biochar properties

Biochar is a "heterogeneous substance rich in minerals and aromatic carbon." As mentioned, the feedstock biomass mainly comprises cellulose, hemicellulose, and lignin-based substances, the non-starch fraction. These three polymers are primarily responsible for physicochemical changes during pyrolysis, which also governs biochar's properties. The degradation process of these polymers varies according to their chemical state. The breakdown of cellulose and hemicellulose is more rapid compared to lignin (Li *et al.*, 2020). Apart from cellulosic materials, the feedstock contains organic and inorganic substances. Inorganic materials account for $<10\%$ of biomass weight that is converted to ash during pyrolysis, whereas the organic fractions that contain carbohydrates, protein, fats, and several secondary metabolites can be restored by polar and non-polar solutions.

Additionally, biomass is substantial water in a free and bound form vaporized during thermal treatment. The operation temperature is the main factor that governs the extent of de-volatilization of the different biomass components. The first component to be eliminated is water (free and bound) (up to 160°C). After that, the extractives get volatilized (at 220°C), followed by hemicellulose that degrades at 220 to 315°C. Cellulose shows high thermal stability and degrades at 315 to 400°C, whereas lignin is the most resistant to degradation and decomposes at 900°C (Kandanelli *et al.*, 2018).

Carbon content, volatile compound content, bulk density, porosity, surface area, carbon stability, presence of heavy metals, nutritional content, pH value, water holding capacity, ash content, polyaromatic hydrocarbon (PAH), elemental composition, electrical conductivity, and cation exchange capacity (CEC) are the measured characteristics for biochar considered for its quality. These quality parameters depend on biomass sources, residence time, heating rates, and temperature. Certain parameters are more critical for assessing the quality of applied biochar. The pH, volatile matter content, ash content, bulk density, water holding capacity, surface area, and pore volume are critical parameters for quality biochar in crop production. For carbon sequestration and restoration of soil fertility per se, carbon stability is an important criterion governing biochar performance. The molar hydrogen to carbon ratio (H/C) is an essential criterion of biochar to measure stability and degree of carbonization.

On the other hand, the molar oxygen to carbon ratio (O/C) determines maturation. An H/C lower than 0.7 suggests good-quality biochar. Similarly, an O/C higher than 0.4 indicates a lesser stability of biochar. Eventually, the H/C and O/C in lignocellulosic biomass are, on average, 1.5 and 0.7, respectively. Hydrogen and oxygen fractions get volatilized during pyrolysis and, eventually, enriched with carbon fractions. That is why the H/C and O/C tend to decrease when biomass is converted into biochar.

Various analytical approaches are employed to characterize biochar at the structural and molecular level, in addition to proximate analysis. These methods mainly aim to determine the relationship between the physicochemical properties of biochar and their behavior in the environment. These techniques are Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD), transmission electron microscopy (TEM), thermo gravimetric and derivative thermal gravimetric analysis (TGA-DTG), solid-state nuclear magnetic resonance (ssNMR), etc. The FTIR is generally used to determine functional groups present in biochar and its structural analysis. It also provides information about structural and functional changes in biochar during biomass conversion. The obtained spectra describe C−H stretching bands associated with aliphatic groups. For the biomass, the peak near 3,300 cm^{-1}, 2,885−2,935 cm^{-1}, 1,740−1,700 cm^{-1}, and 1,645−1,653 cm^{-1} represent H-bonded hydroxyl groups, symmetric and asymmetric C-H stretching, C=O stretching of carbonyl, esters and vibration bands for amides, respectively, characteristic for feedstock materials. While converted into biochar, these peaks change significantly, confirming the transformation (Das *et al.*, 2009). Protein, amine, esters, and biological components in the feedstock can also be identified using FTIR spectroscopy. Using SEM, the surface attributes are determined. It provides surface morphology data that is connected with the relationships between adsorbent and adsorbate. The SEM confirms that one of the important aspects of the preparation of biochar is still residual cell porosity and morphology. The porous surfaces retain a disordered structural shape and contain much of the cell's original morphology (Mohan *et al.*, 2015). The study of surface morphology can also determine any sorption or impregnation over the biochar-like surface characteristic of biochar before and after iron impregnation, surface-modified biochar-like magnetic biochar, clay biochar carbon composite, etc. Unlike SEM, the TEM technique is used to determine the size, composition, and electronic state at high resolution, as well as morphology, morphology, and crystallinity to some extent. As the sample is to be prepared as a thin specimen for analysis, definite sample preparation techniques like ion milling, electro-polishing, or ultra-microtomy are required a few times. TEM can characterize surface-modified biochar as size and morphology change upon derivatization of functional groups present in biochar. Taking the determination of crystallinity, the XRD technique is used the same. Peaks appearing in the XRD pattern signify biochar's specific crystalline or amorphous nature with other minerals frequently detected in biochar formed at high pyrolytic temperatures from forest and agricultural residues. Upon increasing residence time, the intensities of XRD peaks increase due to an increase in

particle diameters with time (Zhang and Gao, 2013). This technique is useful for the characterization of biochar in a non-destructive manner with high accuracy. Another technique, i.e., solid-state ^{13}C NMR spectroscopy, is used to estimate the nature of carbon molecules in the biochar prepared from different feedstocks at temperatures of 350 to 600°C. Two different techniques that are used for ssNMR spectra are cross-polarization (CP) and direct polarization (DP). There are characteristic differences between the CP and DP spectra of the specific functional groups. Signals at 15 and 35 ppm correspond to the alkyl group and signals at 55 to 110 ppm for carbohydrates tend to be larger in CP spectra than in DP spectra. This indicates that CP spectra more efficiently detect alkyl carbohydrate and aromatic C (McBeath *et al.*, 2011). On the other hand, the observability of C is higher in biochar for DP spectra than the CP spectra. This may be due to the low proton content of the condensed aromatic units that form the majority of the molecular structure of biochar (McBeath *et al.*, 2014). Determination of elemental composition, aromatic molecular markers, functional groups, and structural density can provide valuable insight into the quantity of aromatic C present in biochar. These characteristics, however, vary among biochars made from various feed supplies but at comparable temperatures. The chemical makeup of the biochar is mostly determined by its matrix compositions, which are crucial in identifying the biochar's potential as a soil amendment and C sink. The ssNMR spectra demonstrate the effect of feedstock composition and operation temperature on the biochar's aromatic fraction, which can be correlated with their recalcitrance and carbon sequestration properties (Wiedemeier *et al.*, 2015). As biochar formation is a thermal-driven process, the study of dynamics in physical and chemical properties of an increase in temperature is needed. The TGA is used to accomplish such analysis. The TGA aids in proximate analysis, i.e., determination of volatile matter and ash content (Shafeeyan *et al.*, 2011). The pyrolysis characteristics can also be described via feedstocks' TG and DTG curves. The variations in the TG-DTG curve indicate changes in elemental composition during the transformation of biochar from respective biomasses, i.e., a decrease in polarity and surface acidity along with an increase in aromaticity, is observed with rising pyrolytic temperature (Kim *et al.*, 2013). The TG analyses also determine biochar samples' water-holding capacity and stability (conjugation of metal ions with biochar surfaces). Table 23.1 displays the characterization techniques used to determine the physicochemical properties of biochar samples prepared from different waste biomasses.

TABLE 23.1 Characterization techniques of biochar produced from different waste biomasses. Modified from (Amin *et al.*, 2016).

Waste biomass	Pyrolysis technique for production	Characterization techniques	Reference
Rice husk, corn stalk, longan branch, coconut coir	Slow	SEM, TEM	(Nguyen *et al.*, 2022)
Rice straw, maize stover, sugar trash, pine needle, lantana stem, eucalyptus wood	Slow	FTIR, SEM TG-DTG	(Chaturvedi *et al.*, 2023)
Pine, grass species, and citrus waste	Slow	TG-DTG	(Wang *et al.*, 2015)
Oakwood and bark	Fast	FTIR, TG-DTG, XRD, SEM, TEM	(Mohan *et al.*, 2014)
Orange peel	Slow	FTIR, SEM, X-ray fluorescence	(Oh *et al.*, 2012)
Menthol mint distillation waste	Slow	FTIR, SEM	(Saha, Basak, and Banerjee, 2022)
Cotton seed hull	Hydrothermal carbonization	FTIR, TG-DTG, SEM, TEM	(Uchimiya *et al.*, 2011)
Sugarcane bagasse	Slow	FTIR, TG-DTG	(Creamer, Gao, and Zhang, 2014)
Holy basil and sweet basil distillation waste	Slow	FTIR, SEM	(Sarkar *et al.*, 2023)
Water hyacinth	Slow	FTIR, XRD, SEM	(Suryawanshi *et al.*, 2023)

Modified from *Amin et al., 2016*

23.4 Biochar induced carbon sequestration

Soil carbon (C) sequestration is the long-term carbon storage in soil, which could be achieved by applying biochar to soil. Generally, biochar primarily comprises C (50% to nearly 90% by weight), essential for its C sequestration potential. The carbon contents in biochar ranged from 81.2% prepared from bamboo chips to 19.2% in biochar prepared from paper mill sludge (Devi and Saroha, 2015) depending on the nature of feedstock and pyrolysis conditions. Moreover, biochar prepared from crop residues and woody materials contained a higher C content than manure sources. The pyrolysis temperature strongly influences the stability of biochar in soil; the higher the pyrolysis temperature, the higher the stability (Purakayastha *et al.*, 2019). These C contents of biochar also serve as a stable reservoir for C and maintain a higher C saturation level in the soil. On application to the soil, it also acts as a sink of C that enables it to capture and retain C over a longer period, preventing its loss to the atmosphere as CO_2. Thus, this surplus C can be effectively sequestered, contributing to an overall increase in soil C stocks and mitigating the net increase in CO_2 in the atmosphere. Furthermore, biochar's high C content, combined with its recalcitrant nature (because of its aromaticity, presence of amorphous structure and turbostatic crystallites, rounded structures, and reduced accessibility to decomposers), reduce its accessibility to decomposers by allowing it to persist in the soil for extended periods without significant C loss (Weng *et al.*, 2022). This longevity ensures that the sequestered C remains stored in the soil, providing a reliable and long-term solution for C sequestration. Furthermore, the higher stability of biochar in soil is also due to strong interactions with mineral surfaces. Biochar interacts with native soil organic matter (SOM) in a complex way; sometimes, biochar shows a positive priming effect, a negative priming effect, or no effect on native SOM. This depends on the feedstock type, pyrolysis temperature, and soil level of organic matter. The soils richer in organic matter status provide a positive priming effect of native SOM due to biochar addition and vice versa (Purakayastha *et al.*, 2019). The role of biochar in soil carbon sequestration is very complex. It depends on several interconnected mechanisms, *viz.* soil organic carbon (SOC) input, soil microbial community, protection against microbial decomposition, degree of soil aggregation, water and nutrient retention, stabilization, and conversion of labile carbon to recalcitrant carbon. Moreover, the maximum capacity of carbon sequestration through biochar soil amendment in world agricultural soils (1,411 million hectares) is estimated to be about 428 Gt C, assuming a maximal 10% biochar C by soil weight for the first 30 cm soil layer alone (Lee and Day, 2013). The highest technical potential sequestration density (sequestered carbon per unit land area of the country) of a country like India is 27 Mg C km^{-2} $year^{-1}$). These high sequestration densities are due to a combination of high fractions of land area under cropland, high residue crops dominating, and high-intensity agriculture with a combination of high yields and widespread multicropping system (Karan *et al.*, 2023). The impact of biochar application on soil organic carbon has been summarized in Table 23.2. Applying biochar increases soil carbon inputs by binding organic carbon to soil particles, reducing soil

TABLE 23.2 Soil organic carbon is affected by the application of different types of biochar.

Type of biochar	Rate of application	Type of soil	Soil organic carbon	Reference
White lead tree wood	5% (w/w)	Acidic Ultisol	Increase in soil organic carbon (33.1%)	(Jien and Wang, 2013)
Sugarcane bagasse	4.2 t ha^{-1} yr^{-1}	Oxisol	Increase in soil total organic carbon stock by 2.35 ± 0.4 t C ha^{-1} yr^{-1}	(Lefebvre *et al.*, 2020)
A mixture of green waste compost and residual biomass	12 t ha^{-1} on a dry weight basis	Luvisol	Increase in soil organic carbon (30%)	(Nobile *et al.*, 2022)
A mixture of cottonseed husk (30%) and rice husk (70%) at 400°C for 4 hours.	90 Mg ha^{-1}	Calcareous soil	Increase in soil organic carbon (63%)	(Ding *et al.*, 2023).
Maize straws (at the temperature of 450°C under in a vertical kiln)	15 t ha^{-1}	Calcareous cinnamon soil	Increase in soil organic carbon (10.7%)	(Ma *et al.*, 2023)
Biochar	90 t ha^{-1}	Salt-affected soil	Increase in soil total organic carbon stock (198.33%) and soil total inorganic carbon stock (16.03%) (↑)	(Liu *et al.*, 2024)

respiration, and increasing the soil carbon sink or carbon storage. However, these phenomena largely depend on biochar's physical and biochemical characteristics, land use, soil moisture, and temperature conditions (Gogoi *et al.*, 2020). Applying biochar is a crucial step in controlling SOC, not only because it directly raises carbon input and modifies SOC's efficacy but also because it affects the transformation of the soil carbon pool (labile to recalcitrant), which in turn affects soil carbon fixation and greenhouse gas emissions. Differences in the type of soil and biochar, cropping system, and other conditions can cause changes to the physicochemical properties of soil and thus affect SOC mineralization rates to varying degrees. Wang, Xiong, and Kuzyakov (2016) reported that the mean residence time (MRT) of biochar labile C fraction (pool size 3%) was 108 days, while the MRT of biochar non-labile C fraction (pool size 97%) was 556 days in a meta-analysis (n = 128 observations) study. They further suggested that about 97% of biochar C could be sequestered in soil for a long time. It is worth noting that the specific mechanisms and their relative importance overall, biochar's ability to physically protect labile C, aggregate formation, and microbial communities collectively contribute to stabilizing labile C in the soil, fostering long-term C sequestration.

23.5 Biochar-induced soil improvement

23.5.1 Soil physical properties

Numerous soil studies have shown that biochar has a greater positive influence on physical attributes than chemical indicators (Oladele *et al.*, 2019). By adding biochar to the soil, its physical properties in terms of bulk density, porosity, water content and micro-aggregate formation, permeability, and saturated hydraulic characteristics are all improved (Zanutel *et al.*, 2024) (Table 23.3). This led to a decrease in nutrient leaching, an increase in soil microbial activity, and an increase in nutrient availability, thus ultimately helping to improve plant growth as it became easier for crop roots to penetration and absorp nutrients (Yang, Wang, and Sun, 2021).

Studies have shown that biochar reduces the bulk density of soil (Dantani, Maigida, and Mono, 2024). Bulk density indicates the packing or arrangement of soil particles and is directly related to soil tightness. Soil with low bulk density increases the run release and the retention of nutrients and decreases soil components. Due to the porous structure of

TABLE 23.3 Effect of biochar application on recipient soil physical health.

Biochar	Temp (°C)	Soil type Country	Rate	MWD	Aggregate stability	WHC	Soil porosity (%)	BD	Reference
Southern yellow pine	400 °C	Acidic Ultisols	5%, 10%, 15%, and 20% (w/w)	—	—	—	(↑) 50%	(↓) 40%	(Chang *et al.*, 2021)
Paper fibre sludge and grain husks	550 °C	Haplic Luvisol	0, 10 and 20 t ha^{-1}	—	—	—	(↑)12%	(↓) 12%	(Toková *et al.*, 2020)
Wheat Straw	450°C	Red Soil/ China	40 t ha^{-1}	—	—	9.7-17.1% (↑)	—	0.43 g cm^{-3}(↓)	(Jin *et al.*, 2019)
Wheat straw	500 °C	Acidic soils, China	4% w/w	—	—	—	—	18% (↓)	(Malik *et al.*, 2018)
Wheat straw	350 −550°C	Red Soil (China)	40 t/ha	28.02% (↑)	32.79% to 69.71% (↑) macro-aggregates	—	—	—	(Liu *et al.*, 2014).
Rice husk in combination with N fertilizer	350 −400°C	Alfisol/ Nigeria	12 t ha^{-1}	—	23% (↑)	25% (↑)	—	18% (↓)	(Oladele *et al.*, 2019)

MWD: mean weight diameter of soil aggregates; WHC: water holding; Ksat: saturated hydraulic conductivity; BD: bulk density; ↑: increase; ↓: decrease.

biochar and its lower density (0.05−0.57 kg/m^3) than mineral soil, the application of biochar in soil resulted in a lowering of bulk density (Dorjee *et al.*, 2024). However, several factors like the composition of biochar, its size, application rate, and characteristics of receiving soil influence the impact of biochar on lowering the soil bulk density. Studies reported that biochar reduces the bulk density of salt-affected soil up to 0.7 to 26.1%. Studies showed that impacts are short-lived at higher application rates, and small and medium size particles are more effective in reducing the bulk density than larger particle sizes. Mechanisms behind the reduction in bulk density after biochar application include increased soil cation exchange capacity, biochar-organic matter-mineral particle complex development, soil particle entanglement, and cementation due to root exudates (Yuan *et al.*, 2023).

Studies showed that biochar application increases the porosity of the recipient soil. Due to the high surface area and porous nature of biochar, its application increases the pore structure of the soil. Moreover, applying biochar alters the soil pore distribution. It reorganizes the soil pore, which increases the soil porosity, water, and air circulation, decreases soil compaction, and ultimately increases soil fertility (Y. Zhang, Wang, and Feng, 2021). A higher border surface area for more microbial activity and improved root development are the benefits of increased soil porosity, which also relaxes the soil and indirectly increases porosity. Research revealed that high-temperature-prepared biochar had a greater impact on enhancing soil porosity (Andrenelli *et al.*, 2016). This may be attributed to the higher surface area and pore space and reduction in volatile material in biochar prepared at high temperatures. However, Jien and Wang (2013) reported that biochar application at a higher rate (5%) decreased the soil porosity, whereas it increased at a lower rate (2.5%), and they opined that biochar could manipulate the inter-particle contact of soil particles by a loosening effect. Studies indicate that biochar addition to soil contributes to developing new pores. Due to the increase in soil porosity, biochar application also increases crop productivity. Moreover, biochar addition also increases the total porosity in frozen soil. Various factors such as the morphology of biochar, rate of application, pyrolysis temperature, and biochar soil particle interaction determine the soil's increase or decrease of porosity (Alghamdi, 2018).

Because biochar has a high porosity and surface area, it also lowers soil water permeability barriers, alters the water residence duration and flow channel, and increases the soil water-holding capacity. The benefit of adding biochar in surging the water holding capacity is greater in sandy soil than clay soil due to the poor water retention capacity of sandy soil (Ibrahimi and Alghamdi, 2022). Biochar helps in increasing plant transpiration, which increases plant water usage efficiency. Because of its increased soil water retention property, biochar application is helpful in locations with limited water resources. A three-year field experiment study revealed that biochar application increased the soil water retention capacity at matric potentials of −0.033 and −1.5 MPa (Yafu Zhang, Wang, and Feng, 2021) and increased the available water content in the soil. Surface hydrophobicity and pore volume are the main factors influencing the effect of biochar on modifying the soil water retention capacity (Mao, Zhang, and Chen, 2019).

Additionally, when biochar is added, due to an increase in the intra- and inter-pore, the water storage spaces of soil are increased. Because biochar is a black particulate substance, adding it to soil darkens the color, influencing the soil's temperature, heat, and surface reflectivity. The Munsell color value of soil increased with an increase in biochar application rate. Applying biochar causes the soil to become darker, which raises the temperature and promotes crop emergence and yield.

Biochar application reduces the thermal conductivity of the soil and thus reduces the transfer of surface heat to the subsurface layer in the daytime. In contrast, soil releases heat during nighttime, thus stabilizing the soil temperature. This decrease in soil thermal conductance may be due to increased organic matter content in the soil. Biochar application increases the topsoil temperature and thus alleviates topsoil fluctuation in saline-alkaline soil. In field experiments, biochar application at a depth of 5 cm increases the soil temperature (Zhang *et al.*, 2013). However, further research is needed to understand the relationship between biochar characters and soil temperature.

23.5.2 Soil chemical properties

Various chemical and microbiological activities in the soil are determined by the soil pH, a crucial parameter governing crop growth and nutrient availability. Since biochar is alkaline by nature and contains ash and carbonates of various exchangeable bases, applying biochar to soil raises its pH, enhancing the availability of a variety of macro- and micronutrients in the soil. Thus, biochar acts as a potential liming in reclaiming the acid soil and improves the soil fertility (Table 23.4). In general, after the application of biochar, the H^+ and Al^{+3} present in the soil solution are exchanged, thus reducing their concentration, which imparts soil acidity. Besides laboratory incubation studies, biochar also increases the soil pH from 3.89 to 4.05 in four-year field applications, indicating the long-term beneficial effects of biochar. However, biochar application did not change the soil pH if the soil moisture content was high. This may be due to the prevalence of reducing elements as an increase in moisture content leads to oxygen-deficient conditions, which favors the decrease in soil pH.

TABLE 23.4 **Response of biochar application on changes in chemical properties of recipient soil.**

Biochar	Temp (°C)	Soil type/ Country	Rate	Impacts on soil chemical properties	Reference
Cotton stalks	420°C	—	1 % (w/w)	(↑) in SOC (up to 1.2 times) and (↑) in pH and EC up to 5 and 47%, respectively.	(Abid *et al.*, 2017)
Straw, woodchips, and wastewater sludge	500°C	Acidic Ultisol/ China	0, 2, 4, 6 % (w/w)	(↑) in total C (94%); (↑) in soil pH (up to 2.33) and (↓) in exchangeable acidity (up to 100%) but no significant change in CEC	(Zong *et al.*, 2018).
Cacao shell biochar	400 and 500 °C	Sandy loam Ultisol, Indonesia	15 t ha^{-1}	(↑) in pH, CEC and acid-neutralizing capacity.	(Cornelissen *et al.*, 2018)
Crushed Acacia seyal charcoal	500°C	—	7.3-10 tons ha^{-1}	Reduction in exchangeable calcium and CEC without affecting soil pH	(Deng *et al.*, 2017).
Corn cob feedstock solely and co-applied with compost	400 and 500°C	Sandy clay loam, Uganda	(10 t/ha and 20 t/ha)	(↑) in pH, CEC, and SOC	(Apori and Byalebeka, 2021)

TOC and SOC: total and soil organic carbon; ↑: increase; ↓: decrease.

Moreover, a few studies have also indicated the lowering of soil pH due to adding biochar. In addition, the study showed that biochar produced at lower temperatures considerably decreased soil pH by up to 3.0% (Yuan *et al.*, 2023). Biochar produced at low temperatures releases H^+ ions from various oxygen-containing functional groups (e.g., −COOH, −OH) present in it. Hence, continuous in situ monitoring of soil pH is required in biochar-amended soil.

Adding biochar to soil improves its cation exchange capacity (CEC). CEC measures the soil's capacity to absorb, retain, and exchange cations. Increasing CEC will improve nutrient use efficiency and reduce nutrient loss. Soil with high CEC showed higher buffering capacity upon adding alkaline or acidic chemicals (He *et al.*, 2023). Due to the presence of various oxygenated or alkaline groups (e.g., -OH, -COOH, -CO) in biochar, its addition to soil increases the adsorption capacity of soil cations and thus increases the soil CEC.

Moreover, upon contact with water and oxygen in the soil, the surface of the freshly added biochar undergoes various oxidation procedures, enhancing the negative charge and CEC. The type of biochar, the temperature at which it is pyrolyzed, and the rate at which it is applied all affect how well it enhances CEC. Biochar made from wood showed a greater improvement in CEC than biochar made from straw. When biochar is applied more frequently, CEC is enhanced more. Similarly, biochar generated at a lower temperature performed better in raising the CEC than biochar produced at a somewhat higher temperature. Application of biochar in field study also reported enhancement of CEC. CEC-enhancing effects on biochar were found to be significant in mild non-calcareous soil. However, biochar application in organic soil did not show any noticeable impacts as the soil already has high CEC due to the content of high organic matter (Glaser *et al.*, 2015)

Soil redox potential (Eh) regulates the nutrient dynamics, metal dynamics, physiology, and phenology of crop and greenhouse gas emissions (Husson *et al.*, 2016). Biochar can be both a reluctant and an oxidant. Since biochar application changes the soil bulk density, porosity, and soil hydraulic properties, which are associated with soil redox statutes, the redox status of the soil is also influenced by the biochar application. Awad *et al.* (2018) showed that biochar reduces the Eh of flooded soil; however, the extent of reduction depends on the biochar's pyrolysis temperature. However, Khatun *et al.* (2021) reported that biochar acts as an electron acceptor and increases the Eh of salt-affected soil. Hence, the impacts of the complex interactions of biochar, organic carbon, and microbial community on the Eh should be elucidated within this context.

Applying biochar aids in raising and stabilizing the SOC content, improving soil productivity over time, and reducing greenhouse gas emissions. When added to soil, biochar catalyzes the polymerization of organic particles, producing soil organic matter (Sun *et al.*, 2021). In addition, higher surface area and high pore content in biochar also enhance the

accumulation of more soil organic carbon. Compared to municipal and food waste-derived biochar, straw-derived biochar showed higher carbon sequestration potential (Al-Wabel *et al.*, 2018). However, a long-term successive biochar application study is required to assess the accumulation and stabilization of SOC by biochar.

Biochar addition also mitigates the salinity and sodicity of soil. Due to low organic matter content, saline soils are less structurally stable, and biochar addition can reduce salt stress and increase plant growth (Yuan *et al.*, 2023). In general, biochar addition to saline soil increases the soil structure, facilitates water infiltration, and reduces the sodium level in the soil.

Moreover, biochar's CEC balances the soil ions and thus reduces the salt stress. Moreover, biochar addition in saline soil increases microbial activity and enhances the activity of salt-tolerant microorganisms, which helps improve soil health (Kudakwashe *et al.*, 2022).

23.5.3 Nutrient availability

A variety of stresses are lessened by biochar, which improves soil nutrient cycling (Xia *et al.*, 2023). Due to its porous structure and abundance of oxygenated functional groups, biochar's surface properties enable it to effectively retain nutrients, reduce nutrient loss from the soil, improve the structure of the soil microbial community, and promote nutrient cycling (Kul *et al.*, 2021). Generally, fertilizers containing nitrogen (N) have been acknowledged to help stressed soil, and yet too much N can cause water pollution and soil acidification. Conversely, biochar has benefits for enhancing soil. In addition to directly increasing N content, biochar aids crop N uptake by retaining N and reducing N leaching loss (Xia *et al.*, 2023). Additionally, Azadi and Raiesi (2023) found that the addition of sugarcane bagasse biochar increased potential net ammonification (177−218%), nitrification (70−83%), and N mineralization (92−110%), all of which improved urease activity and microbial biomass N (MBN) in saline Pb-polluted soils. Using biochar can effectively minimize surface runoff, the main source of nitrogen loss.

By encouraging the nitrogen metabolism process, adding biochar can help lower nitrogen loss. First, by raising soil urease activity and the number of ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA), biochar can hasten the conversion of organic nitrogen into ammonia. Nitrifying bacteria can exploit the increased ammonia nitrogen to generate nitrate nitrogen, which roots can use (Liu *et al.*, 2022). Zwieten *et al.* (2015) claim that functional groups in biochar can exchange nitrogen with positively or negatively charged ions, and porous structures can hold onto nitrogen to help trap nitrogen. Specifically, carboxyl can adsorb nitrogen from ammonia through electrostatic attraction, preventing denitrification and reducing ammonia and nitrous oxide emissions in soil. Because biochar interacts with Al and Fe minerals to immobilize P, it also raises the pH of acidic soils, allowing accessible P to be released more easily (Maru *et al.*, 2020). Biochar can increase alkaline phosphatase activity and accessible P content by upregulating the expression of alkaline phosphatase (phoD) in response to higher soil pH (Yang and Lu, 2022).

Additionally, biochar can enhance total soil P (Egamberdieva *et al.*, 2022) and P uptake by plant roots by increasing the number of bacteria that solubilize tricalcium phosphate (Dey *et al.*, 2021). This is particularly true when there is salinity in the soil. Zong *et al.* (2018) claim that adding biochar to extremely acidic soil increased the quantity of available P and total C. Among the biochar produced from various feedstock materials (straw, woodchips, sludge, etc.), straw biochar had the highest K content, increasing the amount of K available in the soil (Aller, 2016). When biochar was applied to a subtropical sandy Ultisol, fixing P in the biochar matrix led to an almost 50% reduction in the leaching loss of P (Ukwattage *et al.*, 2020).

Similarly, Kuo, Lee, and Jien (2012) discovered that sawdust biochar applied to coarse-textured sandy loam soil in Taiwan decreased the leaching of NH_4^+ and K^+ by 30% and P leaching by 68%. Biochar can be a great matrix for making fertilizers that release nutrients gradually because of its large specific surface area, porosity, and presence of several functional groups (slow-release fertilizers and controlled-release fertilizers). Using biomass and providing resources for preserving the environment is feasible by co-applying biochar, co-pyrolyzing, or co-composting it with synthetic fertilizers (Marcińczyk and Oleszczuk, 2022). Biochar is highly attracted to nutrients in soil and water, especially N and P. Several techniques have been suggested to create biochar-based SRFs that work, including encapsulation, granulation, co-pyrolysis, and impregnation.

23.5.4 Soil biological properties

23.5.4.1 Effects on microbial community

Soil microbial communities can be optimized by applying biochar, which increases biological functioning, diversity, and enzyme activity (Azadi and Raiesi, 2023; Zhao *et al.*, 2024). The relationships between biochar and soil

microorganisms are governed by several intricate processes that rely on several variables, including the type and rate of biochar application, the nature of the soil, and the functional diversity and composition of soil microbes (Dai *et al.*, 2020). Following assimilation, biochar modifies the soil's physical and nutritional availability, altering the structure of the bacterial and fungal communities. Herrmann *et al.* (2019) proposed four mechanisms for the interaction of biochar with microbial communities: (1) increased nutrient and labile organic carbon input; (2) decreased nutrient leaching and contaminated toxicity; and (3) enhanced water holding capacity. High specific surface area (SSA) and micro-porosity allow the biochar to maintain a wide variety of microorganisms and function as a habitat for soil microorganisms, promoting soil microbial activity. The pore structure of biochar may prevent predators or competitors, creating a favorable ecological niche for bacteria and fungi (Herrmann *et al.*, 2019). Following biochar application, the fungal community structure in many soil conditions exhibited a significant shift, but the bacterial community structure typically showed little to no change. This is because bacteria are more adaptable and responsive than fungi. Because of this, some studies asserted that adding biochar to soil only marginally changed the bacterial community's structure. Generally speaking, fungi adapt to new environments more slowly than bacteria. Therefore, when biochar is absorbed into the soil, the fungal community usually experiences significant changes. According to Imparato *et al.* (2016) and Zheng *et al.* (2016), adding biochar generally lowers the amount of fungal abundance by increasing saprophytic competition from easily degradable organic carbon sources and raising the pH of the soil. Thus, fungal diversity decreases and fungal pathogen growth is inhibited (Dai *et al.*, 2018). However, it is generally accepted that adding biochar increases the number of proteobacteria and actinomycetes while reducing the number of chloroflexi and acidobacteria (Cole *et al.*, 2019). The explanation for this is that while chloroflexi and acid bacteria are frequently found in oligotrophic soil with low pH, proteobacteria are primarily found in eutrophic environments, and actinomycetes are known to play a critical role in the turnover of organic matter (Ali *et al.*, 2019). When biochar was applied to weathered soils, the effects on the microbiological and enzymatic activities of the soil were different and inconsistent. As an illustration, studies in acidic Ultisol have found microbial population stimulation brought on by the use of biochar, Oxisol, and Nitisol (Yu *et al.*, 2018; Asfaw *et al.*, 2019). According to Oladele *et al.* (2019), applying biochar to a deteriorated Alfisol caused the rhizospheric bacterial population to be initially stimulated. Nevertheless, after adding biochar to the Alfisol soil, the same study noted an initial suppression of mycorrhizal fungi.

23.5.4.2 Effects on soil enzymatic activity

The enzymatic activity of the soil is impacted by the application of biochar, just as the microbial population is. Soil enzyme activity is a critical metric for assessing soil health because of its high sensitivity to soil contaminants and close correlation with microbial activity (Bandara *et al.*, 2020). Applying biochar can boost the activity of enzymes like catalase and dehydrogenase, which improve stress tolerance (Liu *et al.*, 2022). According to Nie *et al.* (2018), soil enzymes are also necessary for the cycling of nutrients like N, P, and K and their effect on plant nutrient uptake. Studies have shown that adding biochar improves enzyme activity in nutrient cycling, such as phosphatase, sucrase, and urease (Cao *et al.*, 2023). According to Chen *et al.* (2020), adding various biochars increased the soil's urease activity by 19 to 213%, sucrase activity by 4.6 to 12.5 times, and catalase activity by 19 to 150.8%. Acidic environments impede the enzyme's activity, which causes the ionic and hydrogen connections in the enzyme's active center to break and the structure of the enzyme to change in three dimensions. According to Campos *et al.* (2020), adding biochar positively correlated soil pH with dehydrogenase activity. Thus, the liming effect of biochar also helps to promote enzyme activity. Several research studies demonstrated the activating effects of applying biochar to soil microbial biomass pools in weathered soil, such as microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN). The stimulatory impact, however, was only noticeable at high rates of biochar application. Studies conducted on degraded soil found a linear relationship between the content of biochar and the enzymatic and microbiological activity of the soil.

23.6 Conclusion

Production of biochar from waste is a novel concept for establishing a long-term sink for atmospheric CO_2 storage. Biochar provides a stable and inert form of carbon with a high mean residence time (MRT) and a low risk of return into the atmosphere. Biochar also effectively improves soil physicochemical and biological properties, directly influencing soil fertility. The high surface area and porous nature of biochar enable them to adsorb or retain nutrients and provide a habitat for beneficial microorganisms. So, biochar plays a significant role in improving nutrient use efficiency by reducing nutrient losses. However, the following points need to be considered for large-scale adoption of biochar by end users.

- Biochar application needs to be well synchronized with the agroecological condition of the application site
- Production of "tailored" or "engineered" or "designed" biochar from easily available feedstock matching local and regional needs
- Practical feasibility of biochar application in agriculture by optimizing rate and frequency through long-term field trials
- Evaluating biochar as C negative technology (C credit) by considering agricultural and environmental footprints.

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Chapter 24

Sustainable solutions: Utilizing agricultural waste for bioplastics and biofibers

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Chapter Outline

24.1. Introduction 431
24.2. Agricultural waste: An untapped resource 432
24.3. Potential of agricultural waste for bioplastics and biofibers 432
24.4. Chemical conversion mechanisms for transforming agricultural wastes into bioplastics and biofibers 434
24.5. Challenges and limitations 435
24.6. Cost and scalability 436
24.7. Environmental impact assessment 437
24.8. Solutions and ongoing research efforts 437
24.9. Conclusion 438
References 438

24.1 Introduction

The widespread use of petroleum-based plastics has led to a global environmental crisis, with plastic waste accumulating in landfills, oceans, and other ecosystems (Geyer, Jambeck, and Law, 2017; Jambeck *et al.*, 2015). The detrimental effects of plastic pollution on the environment, wildlife, and human health have become increasingly apparent, necessitating the exploration of alternative, sustainable solutions (Schnurr *et al.*, 2018; Rochman *et al.*, 2016).

In response to the growing concerns over plastic pollution, there is a pressing need to develop eco-friendly alternatives that can replace conventional petroleum-based plastics (Rujnić-Sokele and Pilipović, 2017; Ehret, 2015). Bioplastics and biofibers, derived from renewable and biodegradable sources, offer a promising solution to this challenge, as they have the potential to reduce environmental impact and promote resource utilization (Kalra, Gaur, and Goel, 2021).

This chapter aims to address the global issue of agricultural waste by exploring its potential as a resource for the production of bioplastics and biofibers (Gironi and Piemonte, 2011; Mostafa *et al.*, 2018). The specific objectives of this chapter are: (1) to provide an overview of the types of agricultural waste suitable for the production of bioplastics and biofibers (Kopecká *et al.*, 2022; Nademo, Shibeshi, and Gemeda, 2023), (2) to discuss the methods and processes involved in transforming agricultural waste into valuable bio-based products (Finkbeiner *et al.*, 2010), and (3) to highlight the potential applications of these bio-products in various industries and their contribution to sustainable development (Averous and Boquillon, 2004; Álvarez-Chávez *et al.*, 2012). By meeting these objectives, this chapter aims to contribute to the ongoing efforts to transition toward a more sustainable and circular economy, thereby enhancing the achievement of the Sustainable Development Goals (SDGs) (Kaza *et al.*, 2018; Kirchherr, Reike, and Hekkert, 2017).

The exploration of utilizing agricultural waste for bioplastics and biofibers production aligns with several SDGs. By promoting the use of renewable and biodegradable materials, this chapter contributes to sustainable consumption and production patterns (SDG 12) (Geissdoerfer *et al.*, 2017; Ghisellini, Cialani, and Ulgiati, 2016), supporting the development of sustainable and resilient infrastructure (SDG 9) (UNIDO, 2024). The replacement of conventional plastics with

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bio-based alternatives can help mitigate greenhouse gas emissions and contribute to climate change adaptation (SDG 13) (Demirbas, 2009; Shen, Worrell, and Patel, 2010). The utilization of agricultural waste can lead to the development of more sustainable and inclusive cities and communities (SDG 11) (Van Wart, Grassini, and Cassman, 2013) and foster economic growth and job creation in the bio-based industries (SDG 8) (Staffas, Gustavsson, and McCormick, 2013).

24.2 Agricultural waste: An untapped resource

24.2.1 Definition and types of agricultural waste

Agricultural waste encompasses a wide variety of byproducts and residues generated from various agricultural activities, including crop production, livestock farming, and food processing. This includes materials such as crop stalks, leaves, husks, bagasse, animal manure, slaughterhouse waste, and food processing discards (Pasinszki and Krebsz, 2021). These materials are often overlooked and underutilized, despite their potential as valuable resources.

24.2.2 Quantification and availability of agricultural waste

The global generation of agricultural waste is estimated to be around 3.1 billion tons per year (Sarkar *et al.*, 2012). However, the exact quantity can vary significantly based on factors such as geographic region, crop type, farming practices, and population density (Rafiq *et al.*, 2016). For instance, in India, the annual production of agricultural waste is estimated to be around 500 million tons (Sakina *et al.*, 2023), while in the United States, it is estimated to be around 335 million tons (Karmee, 2016).

24.2.3 Environmental impact of agricultural waste disposal

Improper disposal of agricultural waste can lead to significant environmental challenges, such as air pollution, water contamination, and soil degradation (Girotto, Alibardi, and Cossu, 2015). The burning of agricultural waste is a common practice in many regions, which contributes to the release of greenhouse gases and particulate matter, negatively impacting air quality (Zhao *et al.*, 2008). Additionally, the leaching of organic matter and nutrients from improperly managed agricultural waste can contaminate water bodies and groundwater, affecting aquatic ecosystems and human health (Ekinci *et al.*, 2020). The accumulation of agricultural waste can also lead to the proliferation of pests and the spread of diseases, further exacerbating the environmental challenges (Toop *et al.*, 2017).

24.3 Potential of agricultural waste for bioplastics and biofibers

24.3.1 Suitability of agricultural waste as a feedstock

Agricultural waste has emerged as a promising feedstock for the production of bioplastics and biofibers due to its abundance, renewable nature, and chemical composition (Vigneswari *et al.*, 2024). These waste materials are rich in cellulose, hemicellulose, and lignin, which can be converted into a variety of bio-based polymers and fibers (Vinod *et al.*, 2020). The utilization of agricultural waste as a feedstock can help reduce the reliance on fossil-based resources and contribute to the development of a more sustainable and circular economy (Figure 24.1).

24.3.2 Benefits of utilizing agricultural waste

24.3.2.1 Environmental advantages

The utilization of agricultural waste for bioplastics and biofibers can offer significant environmental benefits. By diverting waste from landfills or open burning, it can reduce greenhouse gas emissions, air pollution, and water contamination (Capanoglu, Nemli, and Tomas-Barberan, 2022). Additionally, the production of bio-based materials from agricultural waste can have a lower carbon footprint compared to conventional petroleum-based alternatives.

24.3.2.2 Contribution to a circular economy

The integration of agricultural waste into the production of bioplastics and biofibers aligns with the principles of a circular economy, where waste is minimized and resources are reused and recycled (Ali *et al.*, 2023). This approach promotes sustainable resource management, reduces dependency on virgin raw materials, and fosters a more environmentally friendly and economically viable industrial ecosystem (Awasthi *et al.*, 2021).

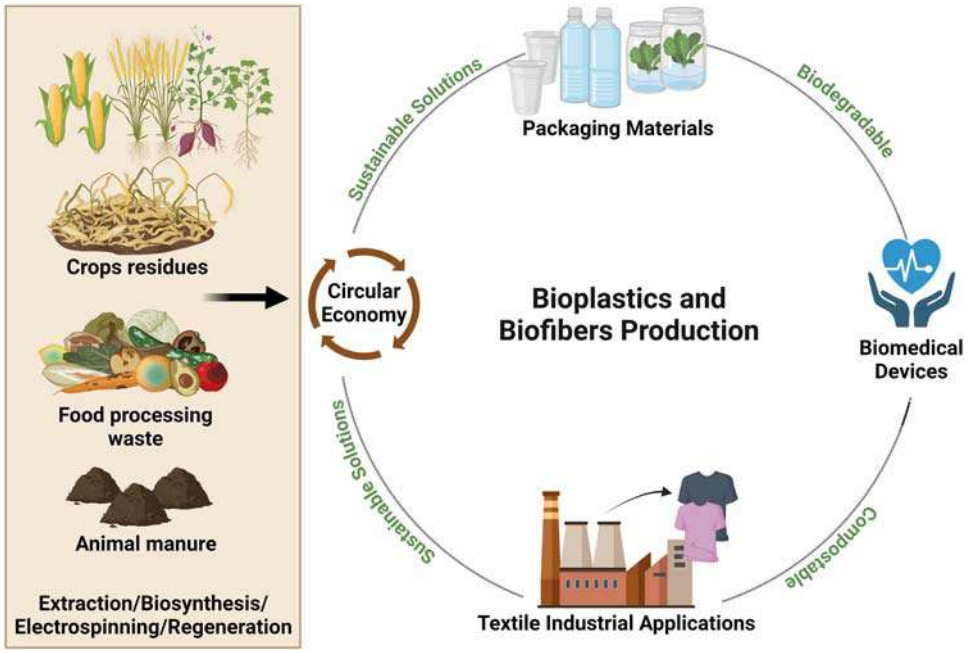


FIGURE 24.1 **Agro-waste utilization for sustainable production of bioplastics and biofibers byproducts and their applications.**

24.3.3 Comparison with conventional materials

Bioplastics and biofibers derived from agricultural waste can offer competitive performance characteristics compared to their conventional counterparts. These bio-based materials can exhibit similar or even superior properties, such as biodegradability, mechanical strength, and thermal stability. Furthermore, the use of agricultural waste can contribute to cost savings and reduced environmental impact throughout the product life cycle (Table 24.1).

TABLE 24.1 **Sustainable alternatives: Bioplastics and biofibers vs. conventional plastics.**

Aspect	Bioplastics and biofibers	Conventional plastics
Source	Derived from renewable resources such as agricultural waste, plants, and algae	Derived from nonrenewable fossil fuels (petroleum based)
Production Process	Produced through biological processes or chemical synthesis using bio-based feedstock	Synthesized from petrochemicals
Environmental Impact	Lower carbon footprint due to renewable feedstock Biodegradable and compostable options available	High carbon emissions during production Nonbiodegradable, leading to plastic pollution
Biodegradability	Bioplastics can break down naturally over time, reducing environmental impact	Conventional plastics take centuries to degrade
Applications	Packaging materials Single-use items Medical devices	Packaging Consumer goods Automotive parts Electronics
Challenges	High production costs Limited mechanical properties compared to some conventional plastics	Dependency on fossil fuels Environmental pollution
Research Areas	Developing innovative molecules and materials from agricultural residues Exploring bio-nanocomposites, filtration, and tissue engineering scaffolds	Advancements in recycling and circular economy approaches

24.4 Chemical conversion mechanisms for transforming agricultural wastes into bioplastics and biofibers

The key steps involved in the chemical conversion of lignocellulosic agricultural wastes into bioplastics and biofibers are as follows.

24.4.1 Lignocellulosic biomass pretreatment

The first critical step is the pretreatment of the lignocellulosic agricultural waste feedstock. This is necessary to disrupt the recalcitrant and complex structure of lignocellulose, which is composed of cellulose, hemicellulose, and lignin. Common pretreatment methods include physical treatments (e.g., milling, extrusion), chemical treatments (e.g., acid, alkali, ionic liquids), and biological treatments (e.g., enzymatic) (Wyman *et al.*, 2005; Haghighi Mood *et al.*, 2013). These pretreatments help improve the accessibility and extractability of the cellulose and hemicellulose fractions for subsequent processing.

24.4.2 Polysaccharide extraction and purification

After pretreatment, the next step involves the extraction and purification of the cellulose and hemicellulose fractions from the pretreated biomass. This can be achieved through techniques such as alkaline extraction, acid hydrolysis, and membrane filtration (Mohamad Zulkifli, Muhamad, and Ang, 2022; Lupoi, 2015). The goal is to isolate the polysaccharides (cellulose and hemicellulose) in a relatively pure form for further conversion.

24.4.3 Polymer formation

The extracted and purified cellulose and hemicellulose can then be converted into various biopolymer materials, including bioplastics and biofibers. For bioplastics, the polysaccharides can be chemically modified or subjected to microbial fermentation to produce biopolymers like cellulose esters, cellulose ethers, or polyhydroxyalkanoates (PHAs) (Kargarzadeh *et al.*, 2012; Koller, 2018).

24.4.3.1 Cellulose-based bioplastics

Cellulose can be chemically modified through esterification or etherification reactions to produce cellulose esters (e.g., cellulose acetate) or cellulose ethers (e.g., hydroxypropyl cellulose), which can then be used as bioplastic materials (Xu *et al.*, 2013).

24.4.3.2 Hemicellulose-based bioplastics

Hemicellulose, such as xylan or arabinoxylan, can also be utilized to produce bioplastics through chemical modification or blending with other biopolymers (Gröndahl, Teleman, and Gatenholm, 2003; Mikkonen and Tenkanen, 2012).

24.4.3.3 PHA production

Certain microorganisms can be engineered or selected to produce polyhydroxyalkanoates (PHAs) from the sugars derived from agricultural waste. These microbially produced PHAs can serve as biodegradable bioplastic materials (Koller, 2018; Możejko-Ciesielska and Kiewisz, 2016).

24.4.3.3.1 Biofiber formation. In addition to bioplastics, the cellulose and hemicellulose fractions can also be used to produce biofibers, such as cellulose nanofibers or nanocrystals. These biofibers can be obtained through various treatments, including mechanical, chemical, or enzymatic processes (Dufresne, 2013; Kargarzadeh *et al.*, 2012).

24.4.3.3.2 Techniques for obtaining biofibers. Biofibers are natural, biodegradable, and renewable materials that have gained significant interest in various industries, including textiles, composites, and biomedical applications. These fibers can be obtained through a variety of techniques, each with its own advantages and challenges.

24.4.3.3.2.1 Extraction from natural sources. One of the most common methods for obtaining biofibers is the extraction from natural sources. Plant-based fibers, such as cellulose fibers from cotton, flax, hemp, and jute, can be extracted through mechanical, chemical, or enzymatic processes (Faruk *et al.*, 2012). These fibers are known for their high strength, low density, and biodegradability, making them attractive for use in composite materials. Similarly, protein-based

fibers can be extracted from animal sources, such as silk from silkworms and wool from sheep (Reddy and Yang, 2005). These fibers possess unique properties, such as excellent mechanical properties, moisture-wicking abilities, and natural luster, which make them suitable for textile applications.

24.3.3.2.3 Biosynthesis. Another approach for obtaining biofibers is through biosynthesis, where certain microorganisms are used to produce the desired fibers. For example, the bacterium *Acetobacter xylinum* can be used to produce bacterial cellulose, which has a highly pure and crystalline structure (Keshk, 2014). Bacterial cellulose has found applications in wound dressings, tissue engineering, and nanocomposites due to its exceptional mechanical properties and biocompatibility. Additionally, various bacteria can be engineered to synthesize polyhydroxyalkanoates (PHAs), which are biodegradable and biocompatible polyesters that can be processed into biofibers (Koller *et al.*, 2017). The production of PHA-based biofibers has been explored for sustainable textile and composite applications.

24.4.3.3.2.4 Electrospinning. Electrospinning is a technique that can be used to produce biofibers, particularly nanofibers, from biopolymers such as chitosan, collagen, and gelatin (Bhardwaj and Kundu, 2010). In this process, a biopolymer solution is subjected to a high electric field, resulting in the formation of ultrafine fibers with diameters ranging from nanometers to micrometers. Electrospun biofibers have high surface-to-volume ratios and can be tailored for applications in tissue engineering, filtration, and drug delivery.

24.4.3.3.2.5 Regeneration from natural polymers. Another approach for obtaining biofibers involves the regeneration of natural polymers, such as cellulose and proteins. For instance, cellulose fibers can be regenerated from wood pulp or cotton linters through processes like viscose or lyocell (Isogai, 2013). Similarly, protein fibers can be regenerated from silk or soy protein (Hu, Kaplan, and Cebe, 2006). These regenerated biofibers can be tailored to have specific properties and find applications in textile and composite materials.

The choice of technique for obtaining biofibers depends on the desired properties, the target application, and the availability of raw materials. Each method has its own advantages and limitations, and the selection of the appropriate technique is crucial for the development of innovative and sustainable biofiber-based products.

24.5 Challenges and limitations

24.5.1 Variability of agricultural waste

24.5.1.2 Impact on quality and performance

The heterogeneous nature and variability of agricultural waste can pose challenges in terms of maintaining consistent quality and performance of the derived bioplastics and biofibers. Factors such as crop type, growing conditions, and post-harvest processing can influence the chemical composition, physical properties, and process ability of the waste materials (Kover *et al.*, 2022).

24.5.1.3 Standardization and characterization methods

Developing standardized methods for the characterization and quality assessment of agricultural waste-based materials is crucial to ensure reproducibility and acceptance in the market (Nair, Lennartsson, and Taherzadeh, 2017). Improved analytical techniques and comprehensive characterization protocols are needed to address the inherent variability and enable the optimization of production processes (Table 24.2).

24.5.1.4 Technological limitations

24.5.1.4.1 Need for advanced processing techniques. The efficient conversion of agricultural waste into high-performance bioplastics and biofibers often requires the development of advanced processing techniques. Challenges may include the need for specialized equipment, energy-intensive processes, and the integration of pretreatment and post-processing steps.

24.5.1.4.2 Exploration of innovative technologies. Continuous research and development are necessary to explore innovative technologies that can enhance the feasibility, scalability, and cost-effectiveness of agricultural waste-based bioplastics and biofibers. Advancements in areas such as biorefinery approaches, green chemistry, and hybrid material synthesis can contribute to overcoming the current technological limitations (Venkatesh, 2022).

TABLE 24.2 Comparative analysis of biofiber production techniques from natural sources.

Technique	Advantages	Disadvantages	References
Extraction from Natural Sources	Utilizes abundant natural materials like feathers, nails, horns, and wool.	Requires specific extraction methods (e.g., chemical hydrolysis, enzymatic treatment).	(Chen *et al.*, 2022; Chilakamarry *et al.*, 2021; Chong, Hassan, and Sultana, 2015; Feroz *et al.*, 2020)
	Biocompatible and biodegradable.	May involve complex purification steps.	
Biosynthesis	Involves microbial production of biofibers.	Requires optimized growth conditions for microbes.	
	Scalable and sustainable.	May have limitations in terms of fiber properties.	
Electrospinning	Produces nanofibers with high surface area.	Requires specialized equipment and expertise.	
	Suitable for tissue engineering, drug delivery, and wound healing.	Limited to certain natural polymers (e.g., zein).	
Regeneration from Natural Polymers	Utilizes existing natural polymers (e.g., cellulose, chitin).	Requires dissolution and regeneration processes.	
	Can be modified for specific applications (e.g., hydrogels, films).	May involve toxic solvents during regeneration.	

24.5.2 Compatibility and performance requirements

24.5.2.1 Achieving desired material properties

The successful application of agricultural waste-based bioplastics and biofibers often requires the achievement of specific material properties, such as mechanical strength, thermal stability, and biodegradability. Tailoring the properties to meet the desired performance standards can be challenging, as it may involve complex blending, modification, or reinforcement strategies (Nida, Moses, and Anandharamakrishnan, 2020).

24.5.2.2 Blending approaches for enhanced performance

Blending agricultural waste-derived materials with other biopolymers or synthetic polymers can be a strategy to enhance the overall performance and expand the applications of bioplastics and biofibers (Rajeswari, Stobel Christy, and Pius, 2021). However, the compatibility and interactions between the different components need to be thoroughly investigated to ensure effective property improvements (Yu, Dean, and Li, 2006).

24.6 Cost and scalability

24.6.1 Challenges in collection, transportation, and preprocessing

The logistics of collecting, transporting, and preprocessing agricultural waste can pose significant economic and practical challenges (Capanoglu, Nemli, and Tomas-Barberan, 2022). Factors such as the geographic distribution of waste sources, storage and handling requirements, and the need for specialized equipment can impact the overall cost-effectiveness of the utilization process (Rathour *et al.*, 2023).

24.6.1.1 Availability and affordability of specialized equipment

The production of bioplastics and biofibers from agricultural waste may require specialized equipment, such as biomass pretreatment units, fermentation systems, and fiber extraction technologies (Kumar Sarangi *et al.*, 2023). The availability and affordability of such specialized equipment can be a barrier to the widespread adoption of these sustainable solutions.

24.6.1.2 Optimization of waste management systems

Integrating the utilization of agricultural waste into efficient and cost-effective waste management systems is crucial for the scalability and sustainability of bioplastics and biofibers production. Optimizing collection, storage, and processing methods can help improve the overall efficiency and reduce the associated costs (Bartolucci *et al.*, 2023).

24.7 Environmental impact assessment

24.7.1 Conducting comprehensive life cycle analyses

Comprehensive life cycle analyses (LCAs) are essential to evaluate the environmental impact of using agricultural waste for bioplastics and biofibers production. These analyses should consider factors such as resource extraction, processing, transportation, and end-of-life management to ensure the true sustainability of the proposed solutions.

24.7.1.1 Identifying environmental hotspots and optimization strategies

Life Cycle Assessment (LCA) studies can help identify the environmental hotspots or areas with the highest impact within the agricultural waste utilization process (Venkatesh, 2022). This information can then be used to develop optimization strategies, such as improving energy efficiency, reducing waste, and enhancing circular economy approaches, to further minimize the environmental footprint (Vinod *et al.*, 2020).

24.8 Solutions and ongoing research efforts

The development of sustainable alternatives to traditional petroleum-based plastics and fibers has become a pressing global priority. Agricultural waste, a ubiquitous byproduct of food production, presents a promising feedstock for the manufacturing of bioplastics and biofibers. Researchers and industry leaders have made significant strides in addressing the challenges and accelerating the adoption of these renewable materials.

24.8.1 Standardization and characterization methods

The successful commercialization of bioplastics and biofibers relies on the establishment of robust standardization and characterization methods. Recent studies have focused on developing comprehensive testing protocols to evaluate the physical, chemical, and mechanical properties of these biomaterials (Nigam, Das, and Patidar, 2021). Advances in analytical techniques, such as thermal analysis, spectroscopy, and microscopy, have enabled more accurate and reliable characterization of the structure, composition, and performance of agricultural waste-derived products (Farid *et al.*, 2021). These standardized methods are crucial for ensuring product quality, enabling fair comparisons, and building consumer confidence in the emerging bioplastics and biofibers market.

24.8.2 Advancement of processing technologies

The processing of agricultural waste into bioplastics and biofibers requires innovative technologies that can efficiently extract, purify, and convert the raw materials. Researchers have made significant progress in developing advanced processing techniques, including enzymatic pretreatment, chemical modifications, and green extraction methods (Rochman *et al.*, 2016). These advancements have led to improved yields, enhanced material properties, and reduced environmental impact. For example, the implementation of microwave-assisted extraction has been shown to increase the extraction efficiency of cellulose from agricultural waste while also reducing energy consumption and processing time.

24.8.3 Formulation optimization and blending approaches

The performance and characteristics of bioplastics and biofibers can be further tailored through the optimization of formulations and blending techniques. By incorporating various agricultural waste-derived components, such as lignin, hemicellulose, and protein-based materials, researchers have developed hybrid formulations with improved mechanical, thermal, and barrier properties (Hao et al., 2024). Additionally, the strategic blending of bioplastics and biofibers with other sustainable materials, such as natural fibers and biodegradable polymers, has led to the creation of novel composite materials with enhanced functionality and versatility (Prithivirajan *et al.*, 2016).

24.8.4 Cost-effective and energy-efficient conversion technologies

The widespread adoption of bioplastics and biofibers hinges on the development of cost-effective and energy-efficient conversion technologies. Researchers have explored various approaches to reduce the production costs and energy requirements, including the utilization of renewable energy sources, the optimization of process parameters, and the implementation of circular economy principles. For instance, the integration of solar-powered biorefinery systems has demonstrated the potential to significantly reduce the carbon footprint and operating costs associated with the conversion of agricultural waste into bioplastics and biofibers (Leong *et al.*, 2021).

24.8.5 Collaboration between academia, industry, and policy-makers

Successful implementation of sustainable solutions for agricultural waste utilization requires a collaborative effort among academia, industry, and policy-makers. Researchers have actively engaged with industry partners to translate their findings into scalable and commercially viable technologies (Malhotra *et al.*, 2023). At the same time, policy-makers have recognized the importance of fostering a supportive regulatory environment, implementing incentives, and developing comprehensive waste management strategies to drive the adoption of bioplastics and biofibers. This multifaceted approach has led to the establishment of research and development hubs, the creation of industry-academia partnerships, and the formulation of policies that accelerate the transition toward a more sustainable and circular economy.

24.8.6 Environmental assessments and life cycle analyses

Comprehensive environmental assessments and life cycle analyses are crucial for evaluating the sustainability and environmental impact of bioplastics and biofibers. Researchers have conducted in-depth studies to analyze the carbon footprint, energy consumption, water usage, and biodegradability of agricultural waste-derived materials (Samanta *et al.*, 2022). These analyses have provided valuable insights into the overall environmental performance of bioplastics and biofibers, guiding the development of more sustainable manufacturing processes and informing policy-makers on the implementation of appropriate regulations and incentives (Kim *et al.*, 2020).

24.9 Conclusion

This chapter has demonstrated the immense potential of agricultural waste as a sustainable feedstock for the production of bioplastics and biofibers, providing an eco-friendly alternative to conventional petroleum-based materials. The abundance of agricultural byproducts globally represents a significant untapped resource that can be leveraged to address the critical issue of plastic pollution, contributing to the achievement of key SDGs. By outlining the various conversion methods and technologies available, as well as the challenges that must be overcome, this chapter offers a roadmap toward a more circular and sustainable future. Ongoing research and cross-sector collaboration will be crucial in advancing these innovative solutions and facilitating their widespread adoption, ultimately paving the way for a greener, more resource-efficient economy. The solutions presented in this chapter offer a promising pathway to a more sustainable tomorrow, underscoring the immense value that can be extracted from agricultural waste through careful processing and valorization.

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Chapter 25

Waste not, mushroom lots: Innovative cultivation methods with agricultural residues

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Chapter Outline

25.1. Introduction 443
25.2. Biology of mushroom cultivation and mushroom types 444
25.3. Agro-waste substrates and their impact on mushroom growth 451
25.4. Innovations, smart farming technologies, and automated cultivation processes in mushroom cultivation 453
25.5. Agro-repurposing of spent mushroom substrate (SMS) in sustainable agronomic practices 455
25.6. Conclusions 461
Acknowledgments 461
References 461

25.1 Introduction

Mushrooms are high proteinaceous foods with low calories, good dietary fiber, vitamins, and minerals. They additionally constitute the only non-animal, unfortified source offering a significant quantity of vitamin D_2 in a single serving and are good reservoirs of nutraceutical compounds (Cardwell *et al.*, 2018). Embedded with these beneficial characteristics, mushrooms are considered "superfoods" that have attracted general consumer preference worldwide. Mushroom cultivation is increasingly being adopted as an agri-business enterprise by the people. Globally, China is recognized as the world's leading manufacturer of edible mushrooms. The consumer preference for mushrooms is growing at an exponential rate (Raut, 2019; Kumar et al., 2022). Modern agricultural residue management protocols and circular agricultural systems now include a sustainable component for mushroom cultivation due to their ability to grow and utilize a wide variety of agro-industrial wastes (Ogbu *et al.*, 2023). Mushroom husbandry thus upgrades the socioeconomic status of the farming community through additional revenue by utilizing farm wastes. Furthermore, the advantages of off-season availability and

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high yields have been possible due to the incredible achievements attained by improved cultivation technologies. Additionally, the leftover spent substrate from mushroom culture is more readily digestible and is valued for a variety of organic and agronomic uses, making mushroom farming a more reliable and sustainable activity (Chen *et al.*, 2022). The present chapter provides an overview of the mushroom cultivation practices, innovations, and advancements in the cultivation technology, multiple valorization purposes of the spent mushroom substrate, and mycoremediation processes by mushrooms.

25.2 Biology of mushroom cultivation and mushroom types

25.2.1 Overview of the mushroom production process

Commercial production of mushrooms involves the following steps.

25.2.1.1 Culture (spawn) production

Cultivation of vegetative mycelium from a chosen mushroom species onto sterilized grain, such as wheat, pearl millet, sorghum, etc., is called spawn. During the process, the mycelia grow through the grain, forming a grain/mycelial mixture, ready to "seed" mushroom compost. The entire process utilizes mushroom tissues or spores to create pure culture, often on agar medium, which are transferred later to sterile grains (acting as carriers) for further multiplication. The development of high-quality spawn is a prerequisite in mushroom cultivation as it serves as the primary input and satisfies better economic benefits by yielding high productivity without any cross-contaminations. Maintenance of sterile conditions and accessibility of spawn substrates influences spawn generation.

The primary steps in spawn production include:

- Preparation of mushroom pure culture
- Substrate preparation
- Preparation of mother spawn
- Commercial spawn production/spawn multiplication.

25.2.1.1.1 Preparation of mushroom pure culture. Multi-spore culture or tissue culture are either utilized in the generation of pure culture of any mushroom variety. Although mushrooms can be propagated by spore culture, not all spores produced could be processed for pure mother culture development as the cultures are highly susceptible to genetic alterations. In the multi-spore culture method, spore print is obtained by collecting the spores through hanging the surface-sterilized fresh fruiting body on a loop of wire above the petri plate/sterilized paper. After being collected, the spores are placed on slants of malt-extract-agar (MEA) or potato-dextrose-agar (PDA) and cultured for two weeks at 25°C ± 2°C. Tissue culture method involves the aseptic transfer of pre-sterilized longitudinally cut bits of tissues from the interior region of the pilus and collar region of the mushroom onto PDA/MEA. Following incubation for one week at 25°C ± 2°C, pure mother cultures are obtained by transferring the mycelium from developing edges to slants (MEA/PDA) (Figure 25.1).

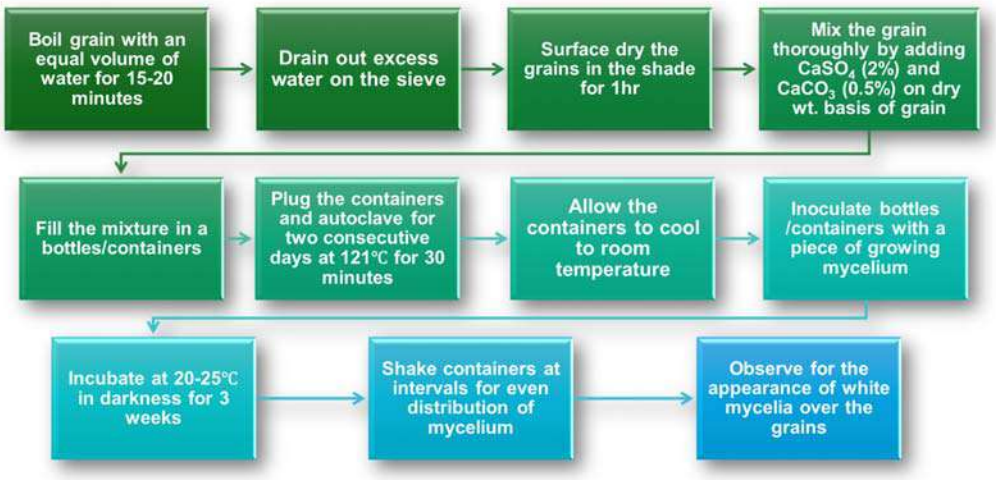


FIGURE 25.1 Substrate preparation and steps in mother spawn production. The flowchart describes different steps in the preparation of substrate and production of spawn mother culture.

25.2.1.2 Substrate preparation

Cereal grains (jowar, wheat, bajra, or rye) or agricultural wastes (rice straw, corn cobs, sawdust, wooden sticks, tea leaves, etc.) are mainly utilized as substrates in mother spawn preparation. Sawdust-based substrates are preferred by shiitake (*Lentinula edodes*) and black ear mushrooms (*Auricularia*), whereas cereal grains are ideal for oyster (*Pleurotus*), white button (*Agaricus bisporus*), and paddy straw mushrooms (*Volvariella volvacea*). Selecting cereal grains free from contamination and infestation by insect pests is important. The cleaned cereal grains are boiled in water, and after draining the excess water, shade-dried for mother spawn production.

25.2.1.3 Preparation of mother spawn

The ready substrate (mixture of boiled grains, gypsum, and chalk powder) is loaded inside glucose/glass/milk bottles or PP bags up to 2/3 volume and sterilized. The sterilized bottles are cooled overnight, inoculated with the pure culture of the mycelium aseptically, and incubated at 25°C. During incubation, bottles are gently shaken for the even distribution of the mycelia (Figure 25.2). Fully colonized mother spawn bottles (obtained after 2-3 weeks) are used as inoculants for commercial spawn bag preparation. However, duration of complete substrate colonization, incubation temperature, storage conditions, and shelf life of mother and commercial spawn vary greatly between mushroom varieties (Table 25.1).

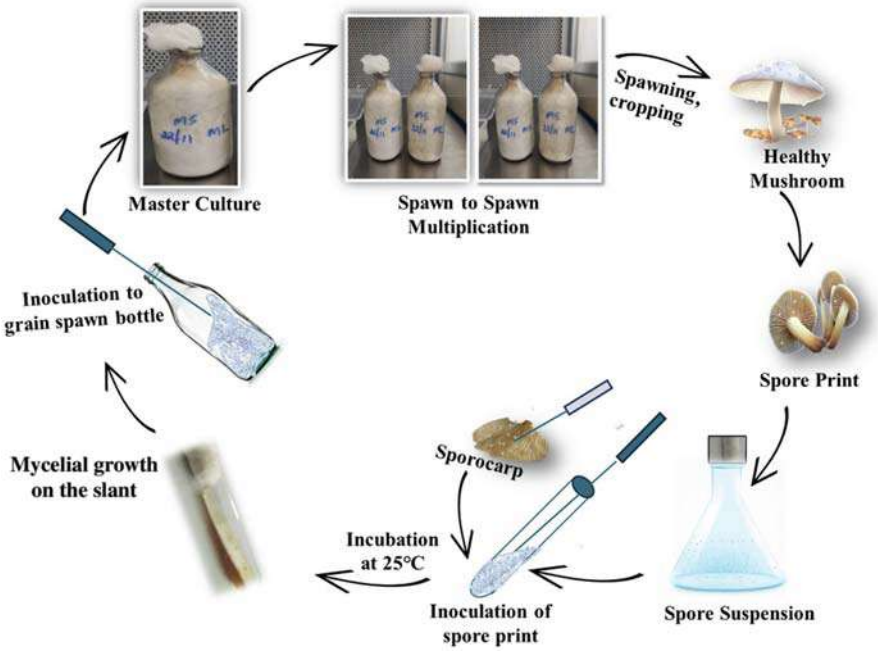


FIGURE 25.2 Development of mushroom pure culture and spawn production. The figure illustrates spawn production using mushroom pure culture.

TABLE 25.1 Parameters for spawn production in different mushroom varieties.

Parameters for spawn production	*Agaricus* sp.	*Pleurotus* sp.	*Lentinula* sp.	*Volvariella* sp.	*Calocybe* sp.
Substrates used in grain spawn production	Paddy/wheat straw	Paddy/bean straw	Sorghum/maize straw	Paddy/maize straw	Paddy/sorghum straw
Mother spawn colonization period	20-21 days	8-12 days	20-22 days	6-7 days	15-17 days
Commercial spawn colonization period	12-14 days	8-10 days	15-16 days	5-6 days	12-14 days
Incubation temperature (°C)	25°C	25°C	25°C	32°C	25°C
Storage temperature (°C) and shelf life of spawn	4°C/60 days	4°C/30 days	4°C/30 days	15°C/<15 days	15-16°C/15 days

25.2.1.4 Commercial spawn production/spawn multiplication

Commercial spawn production is carried out in heat-resistant polypropylene bags. The culture bags are filled with cereal grains, plugged with polypropylene ring neck and non-absorbent cotton, sterilized and inoculated with the mother spawn at the inoculum size of 10 to 15 g of grains per bag. The bags are shaken vigorously for even distribution of the inoculum. The mycelium normally spreads in about 15 to 20 days throughout the grains (Figure 25.3).

25.2.1.5 Substrate (compost) production

Compost serves as a typical nutritional substrate promoting mycelial growth and fruiting body formation. The process of compost making is called composting. Compost is the product obtained through the fermentative degradation of plant residues, organic and inorganic matter by mesophilic and thermophilic microorganisms. During composting, changes occur in the physical, chemical, and biological characteristics of the raw material. The quality of compost has a direct influence on the yield of mushrooms. However, compost made of horse manure and wheat straw is mostly preferred. Alternatively, synthetic compost made from wheat straw and hay is also used. Both natural and synthetic composts require supplementation of gypsum (nitrogen supplement and conditioning agent). Based on the duration of composting, two methods practiced are long (4 weeks) and short (12-15 days) methods. Composting occurs in two stages of phase I and phase II.

25.2.1.5.1 Phase I composting (outdoor composting). This involves mixing and primary decomposition of the raw materials in the outdoor environment. The phase I composting begins with mixing and pre-wetting of basic raw materials (cereal straw, horse manure, etc.) to activate the microbes. Subsequently, the bulk materials are treated with gypsum and nitrogen additions, mixed thoroughly by the turner and stacked within rectangular piles. As naturally occurring microbes continue to grow and reproduce, the aerobic composting process proceeds, producing heat, carbon dioxide, and ammonia as byproducts. The amount of water in the compost pile controls the microbial activity level and heat generation. Furthermore, the organisms require adequate aeration to thrive as well. Thus, water and air content are inter- and inversely related in the composting process. Over-wetting of compost results in a lack of adequate aeration as water molecules occupy air spaces, creating anaerobic condition. Insufficient water results in airy compost. Anaerobes break down organic matter partially, producing heat, carbon dioxide, organic acids, and gases like methane and hydrogen sulfide. The wetted materials are piled in large heaps called windrows. The windrow can be turned and rewetted at 2-3 days interval. Turning benefits with aeration, addition of water to minimize evaporation, even mixing of supplements, and preventing uneven decomposition. The phase I composting lasts for 6 to 14 days. The compost will have a chocolate-brown color, soft pilable straws, and a strong smell of ammonia by the end of phase I, with a moisture content of 68-74%.

25.2.1.5.2 Phase II composting (pasteurization). While phase I composting is a synergistic effect of biological and chemical processes, phase II is purely biological and carried out in specially designed indoor environments. Here, the

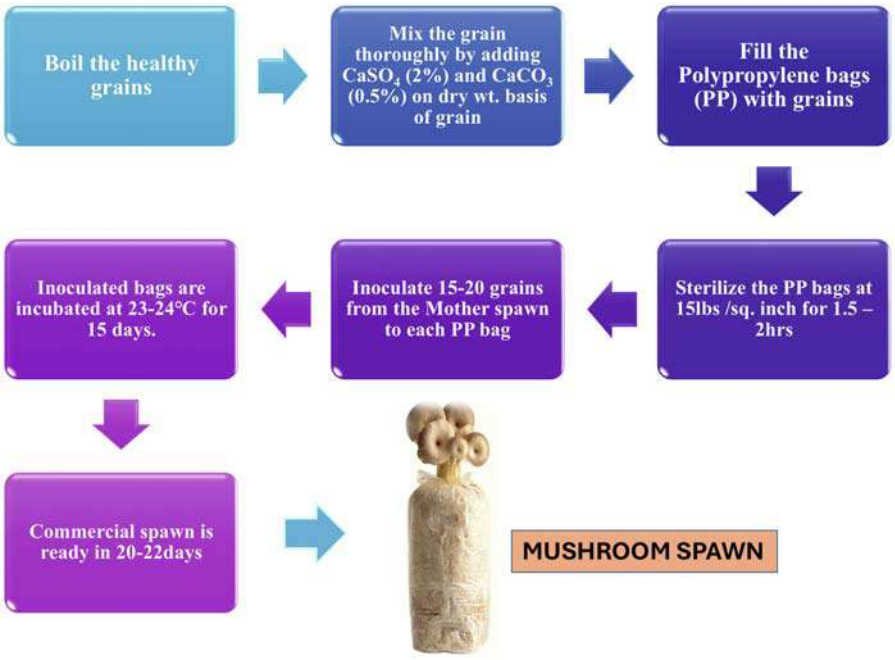


FIGURE 25.3 **Commercial spawn production process.**

compost is pasteurized and conditioned within regulated temperature zones. The procedure allows for controlled indoor monitoring of abiotic variables such as humidity, temperature, and aeration, thereby promoting the selective growth of thermophilic and thermotolerant microbial groups. The two main purposes of phase II composting are pasteurization and removal of ammonia. Pasteurization is done to destroy any insects, pests, nematodes, and fungi that may be present in the compost. The concentration of ammonia formed during phase I composting is high and has an inhibitory effect on the mushroom mycelial growth, hence its removal in phase II is carried out. Maintaining a temperature between 125° and 130°F facilitates efficient colonization by the de-ammonifying organisms. Following pasteurization, the conditioning step involving lowering the temperature of the compost to approximately 75° to 80°F favorable for the growth of microbes before the spawning begins. Thermophilic organisms' growth depends on the availability of usable carbohydrates and nitrogen. The nutrients produced by these microorganisms favor the growth of mushroom mycelia.

25.2.1.5.3 Preparation of non-composted substrates. Mushrooms such as *Pleurotus, Volvariella,* and *Flammulina* are cultivated on non-composted/semi-composted materials. The commercial producers most frequently use cereal straw, specifically wheat straw based on its rigid nature and availability. The selected substrate should be clean and devoid of mold colonization and any preliminary decomposition. The preparation involves chopping the dry straw into pieces of 1-3 inches either manually or with a chipper or shredder, which increases the density of the substrate mass. The chopped straw is pre-soaked in water before being steam sterilized for 2-4 hours at 140°-150° F. Once sterilized, the straw is spread out on a clean surface and allowed to cool. Further, the straw is evenly mixed with spawn and filled into plastic bags, trays, or shelves. Usage of plastic bags is more advantageous in handling and processing. Aeration is provided by making nail-sized holes, and bags are incubated in the dark for mycelial colonization and proliferation. Supplementation of the straw after a full spawn run is beneficial in increasing the yields. Wheat straw is utilized in the successful cultivation of *Pleurotus ostreatus, Panaeolus cyanescens,* and *Psilocybe cubensis* (Suwannarach *et al.*, 2022).

25.2.1.6 Inoculation of substrate (Spawning)

The inoculation of bulk substrates or compost is referred to as spawning. Spawning is achieved by a "mixed spawning method," where the prepared grain spawn is completely and thoroughly mixed with the substrate/compost ensuring all parts of the substrate are equally inoculated, leading to rapid and complete colonization.

25.2.1.7 Colonization of the substrate (Spawn run)

During the spawn run, newly introduced substrate is colonized by the mycelium of inoculated spawn. The spawn run takes place in a controlled optimum environmental conditions of temperature, lighting, and humidity conditions favorable for the growth of mushroom species. Colonization must proceed rapidly to prevent other competitive organisms from becoming established. The complete colonization takes several weeks, during which the mushroom mycelium grows and covers the entire substratum, forming a white, web-like structure. Once the growth is well established, the natural antibiotics secreted checks the growth of competitor organisms. After complete colonization, the spawn-run compost is covered with casing material, which serves as a top dressing on which mushroom fruiting bodies eventually form. The casing layer benefits the growing mycelium by (1) holding and supplying the moisture content promoting mycelial growth and development, (2) preventing drying of substrate/compost, and (3) resisting structural breakdown following repeated watering. Supplementation at casing is important to boost the nutritional content of the substrate. The casing material can be prepared using either cottonseed meal, soybean meal, and/or ground rye or wheat grains. The fully colonized substrate is thoroughly mixed with either of the casing materials (added at 10% level of the dry weight of the substrate). Both the substrate and the supplements must be ensured to be clean and free from contaminants (Dias, Zied, and Pardo-Gimenez, 2021).

25.2.1.8 Initiating fruiting body formation (Pinning)

The differentiation from mycelial stage to primordia formation is referred as pinning/pinhead/fruiting body initiation. Mycelium knots that appear before tiny mushrooms emerge are commonly referred to as pinheads. The primordia formation is influenced by fluctuations in the environmental conditions. Most cultivated mushrooms develop pinheads when the temperature and carbon dioxide content of the room fall below what is optimum for mycelial growth. The mushroom fruiting bodies begins to develop approximately 18−20 days after spawning, when the temperature and moisture levels are ideal. Pinheads proceed to enlarge during the button stage, eventually reaching the size of a mushroom. Increasing the evaporation rate and lowering the humidity is congenial for the developing pins. Fully grown mushrooms can be harvested 18 to 21 days after casing (Sakamoto, 2018).

25.2.1.9 Cropping

Maturation of pinheads to fully formed fruit bodies results after 3 to 5 days of pinhead formation. These fruiting bodies should be harvested before they attain maturity (i.e., when the caps begin to open outward). The cropping cycle is repeated

at every 3- to 5-day period and is referred to as flush or bloom. The first flush is picked in 3 to 5 days with good yields. The second flush is obtained after about 5-7 days with a little less yield. The third flush yields only about 10-15% of production and is of lower quality, because of the infections and infestation by disease-causing pathogens and pests.

25.2.2 Common lignocellulosic mushroom types

An enormous amounts of agro-industrial wastes produced worldwide provides opportunities for their sustainable utilization in growing mushrooms due to their lignocellulosic composition, making them suitable for solid-state fermentation. Most edible mushrooms are saprophytic, possessing enzymes for lignocellulosic conversion and utilization. Mushroom waste generated can further be recycled as fertilizer, animal feed, and medicinal purposes (Cardwell *et al.*, 2018). Agricultural and industrial wastes consist of lignocellulosic biomass (LB) primarily composed of cellulose, hemicellulose, and lignin (Pérez *et al.*, 2002). Cellulose and hemicellulose exist as macromolecular sugars, while lignin is an aromatic polymer (Pérez *et al.*, 2002). The feasibility of edible mushroom cultivation is based on their ability to convert agro-industrial lignocellulosic biomasses by elaborating lignocellulolytic enzymes and utilizing the degraded products to form fruiting bodies. The breakdown of LB is achieved by the combined efficiency of diverse Carbohydrate-Active enzymes (CAZymes) that decompose LBs into smaller molecules through a series of lignin-, cellulose-, hemicellulose-, and pectin-degrading enzymes operating under tight transcriptional control (Kumla *et al.*, 2020). The key enzymes specifically involved in the conversions are depicted in Figure 25.4 and 25.5. Most edible mushroom types' cultivation conditions and importance are summarized (Table 25.2).

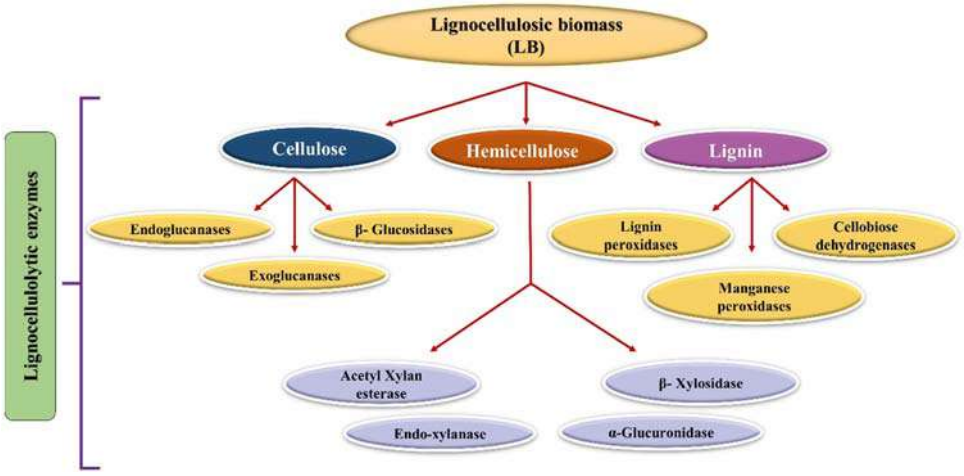


FIGURE 25.4 Illustration of enzymes involved in the breakdown of lignocellulosic biomass. Figure illustrates various enzymes involved in the conversion of complex lignocellulosic substrates into simpler molecules.



FIGURE 25.5 Common edible mushroom types cultivated on lignocellulosic wastes. *Calocybe indica*[1], *Pleurotus ostreatus*[2], *Hericium erinaceus*[3], *Flammulina velutipes*[4], *Ganoderma lucidum*[5], *Lentinus sajor-caju*[6], *Lentinula edodes*[7], *Agaricus bisporus*[8].

TABLE 25.2 Growth parameters, nutritional profile, and beneficial aspects of different mushroom varieties.

Mushroom	Species	Growth parameters			Nutritional profile (in percentage)			Therapeutic activity	References
		Substrate	Growth temp.	Humidity	Carbs	Protein	Fiber		
Button mushroom	*Agaricus bisporus*	Wheat straw/oat straw	22°C-25°C	80-85%	41.6	19-38	3	Anticancer, antioxidant, and immunomodulatory	(Cardwell *et al.*, 2018)
Oyster mushroom	*Pleurotus* spp.	Juncao grass/rice straw	22° C-30° C	80-90%	40-54	10-50	30	Antioxidant, anti-inflammatory, anti-tumor, immunomodulatory, and antimicrobial	(Raut, 2019)
Milky mushroom	*Calocybe indica*	Maize stalk/sugar-cane bagasse	25°C-35°C	70-90%	64.26	17.2	3.4	Antibacterial and antioxidative	(Ogbu *et al.*, 2023)
Lingzhi mushroom	*Ganoderma lucidum*	Sawdust/paddy straw	30°C-32°C	80-85%	3-28	10-40	3-32	Anti-mycotic, anti-aging, anti-diabetic, anti-angiogenic, hepatoprotective, and immunomodulating	(Chen *et al.*, 2022)

25.2.2.1 *Agarics bisporus* (Button mushroom)

The white button mushroom is a basidiomycete member belonging to the order Agaricales. It is a highly cultivated variety worldwide and accounts for 40% of mushrooms produced. *A. bisporus* is not only a valuable food source but also serves as a reservoir of bioactive compounds. The production and consumption of button mushrooms have spiked consistently through the years, and China is the top producer of *A. bisporus*. These mushrooms are characterized with a white cap, brown gills, and fleshy stalk instead of the brownish cap and dark brown gills of the original wild form (Usman, Murtaza, and Nutritional, 2021).

25.2.2.2 *Pleurotus ostreatus* (Oyster mushroom)

Pleurotus species are distinguished by their shell-like cap and designated as "oyster mushrooms" due to their resemblance to oysters. Oyster mushrooms are classified under the family Pleurotaceae. A semicircular to mussel-shaped pileus, a lateral to eccentric stipe, a white to gray spore print, a monomitic hyphae, and a gray to brown hue are characteristic features. The majority of these are saprophytic, while, rarely, some are parasitic. With approximately 70 species, *P. ostreatus* is widely distributed in Asia and other continents of Europe, North Africa, and North America (Raman *et al.*, 2021).

25.2.2.3 *Calocybe indica* (Milky mushroom)

Calocybe indica is classified under the family Tricholomataceae. Milky mushrooms are the initial variety to undergo commercialization, ushering a new era in the Indian agricultural domain (Patel and Trivedi, 2016). Currently, the variety stands as the third most widely cultivated mushrooms in India. *Calocybe indica* thrives in tropical and subtropical regions across the globe, particularly in hot, humid climates. However, indoor cultivation is possible at high temperatures and humidity levels following button and oyster mushrooms. The species has a characteristic appealing milky white sporocarp, with white mushrooms, gills, and stalks. The mushrooms are predictable by their large size, long fibrous stalks, robust and fleshy umbrella-like structures, and a milky white color that persists even when flattened.

25.2.2.4 *Ganoderma lucidum* (Reishi/Lingzhi mushroom)

Ganoderma lucidum is a Ganodermataceae member with a large, dark, glossy exterior and a woody texture (Wachtel-Galor *et al.*, 2011). The Lingzhi mushroom is distinguished by its kidney-shaped cap and stem, which is attached at the edge, leading to a distinctive fan-like shape. When fresh, the mushroom has a soft, cork-like texture and a flat appearance. The fungus thrives in the mycelium structure within the wood of living and deceased trees, exhibiting a tough, leathery, and woody exterior (Mohammadifar *et al.*, 2020).

25.2.2.5 *Auricularia* (wood ear mushroom)

The *Auricularia* mushroom is also known as the wood ear mushroom and has a unique texture. While most mushrooms are smooth and fleshy, the *Auricularia* mushroom has a gelatinous and slightly crunchy texture, resembling the texture of an earlobe (Xu *et al.*, 2021). Brown fruiting bodies with lustrous caps are the typical characteristic features. Ventral surface pores display a spectrum of colors from creamy to white, which changes when physical damage is experienced (Wu *et al.*, 2014).

25.2.2.6 *Lentinula edodes* (Shiitake mushroom)

Growing on fallen wood in a warm, humid environment, *L. edodes* is a wood-decaying basidiomycete. It has a rich flavor and several medicinal applications. Annually, >130,000 tons of *L. edodes* are produced, of which 45% are sold fresh, while the remaining 45% are dried (Bisen *et al.*, 2010). Shiitake has wide geographic distribution extending beyond northeast Asia.

25.2.2.7 *Volvariella volvacea* (Straw mushroom)

Paddy straw mushrooms (*Volvariella volvacea*/Chinese mushroom) are among the third largest cultivated varieties. Because it grows at relatively high temperatures, *V. volvacea* is also commonly known as the warm mushroom. Volva gets its name from the term "wrapper," which describes the wrapping that envelops the fruiting body entirely during the young plant's development.

25.3 Agro-waste substrates and their impact on mushroom growth

25.3.1 Global availability and estimates of agricultural and agro-industrial residue biomass

Growing populations have increased demand for agricultural products, which has led to a significant output of agro-industrial wastes (Kumla *et al.*, 2020). The agro-industrial residues are utilized as sustainable energy sources for various industries including mushroom cultivation. Currently, 750 million metric tons of biomass residue are produced annually. In contrast, 230 million metric tons of agricultural biomass residues are estimated annually (Vaish et al., 2022). A major contributor for agro-industrial wastes are food losses during harvesting and retail junctions. Asia is the largest contributor for agro-industrial waste (47%), followed by North America (29%), Europe (16%), Africa (6%), and Australia (2%) (Cherubin *et al.*, 2018).

25.3.2 Sources of agro-based wastes as mushroom substrates

Most of the agricultural, forest, industrial, and kitchen wastes are rich in lignocellulosic contents cellulose, hemicellulose, lignin, and pectin and serve as ideal raw materials for the production of mushrooms (Kamthan and Tiwari, 2017). These agro-industrial byproducts have great potential to produce valuable food products such as mushrooms based on primary yield, biological efficiency, and morphological characteristics (Singh Baghel, 2020). Incorporating such sustainable practices can reduce the organic waste residues in the environment and addresses various other issues related to health and the economy of the country (Dashtban, Schraft, and Qin, 2009).

25.3.2.1 Vegetable and fruit wastes

Global fruit and vegetable waste production amounts to 1.3 billion tons annually during various stages of processing, storage, and handling. Various fruits and vegetable peels are considered due to their cost-effective nature, resulting in enhanced mushroom biomass, yield, and bioactive components accumulation (Otieno *et al.*, 2022). Pineapple, citrus fruit, banana, and papaya peels have been successfully utilized for cultivation of *Pleurotus* spp. and *Russula* spp. Similarly, vegetable peels of various gourds, drumsticks, potato, pumpkin, leafy waste, and carrots demonstrated better results.

25.3.2.2 Crop-based and processing-based agro-industrial residues

Agriculture crop residues include field-based and process-based residues. Based on statistical reports, of the 683 million tons of crop waste generated, around 178 million tons are utilized for compost, fodder, biogas, and fuel production. Major crop residues generated in India are from cereal crops, followed by fibrous crops, pulses, oilseeds, and sugarcane. Process-based residues include husks, seeds, cobs, stalks, shells, and straw that are obtained as wastes during the post-harvest of crops. The first edible mushroom was cultivated using paddy straw in India. Common mushrooms cultivated using crop residues like paddy straw, wheat straw, barley straw, fiber/coir, sunflower stalk, soybean stems, and corn stalks are button, oyster, paddy straw, and milky white mushrooms. These crop residues are abundant in lignocellulosic components at a 30:1 C:N ratio contributing to the adequate nutritional profile of mushrooms. However, the percentage of hemicellulose, lignin, and pectin directly impacts the biomass and growth of mushrooms.

25.3.2.3 Anaerobically digested waste and agro-residues

The solid effluent (digestate) resulting after complete anaerobic digestion could be utilized to produce value-added foods. The approach facilitates efficient utilization of organic wastes and averts nutrient dumping into landfills, redirecting them for the production of safe and protein-rich foods like mushrooms (O'Brien *et al.*, 2019). Digestate mixed with other agro-residues like wheat straw, millet supplements, poultry litter, grass silage, feedstock, corn waste, jute caddis, and wood chip bedding materials resulted in increased yield, improved growth of fruiting bodies, and better nutritional quality in oyster mushrooms (Figure 25.6). The method is extensively used in the cultivation of *Agaricu*s and *Pleurotus* sp. (Stoknes, Beyer, and Norgaard, 2013).

25.3.2.4 Influence of substrate composition on growth and yield

The quality of mushroom directly depends on the composition and type of substrate utilized. Mushrooms are highly specific in their substrate requirements. *Volvariella volvacea* prefers a substrate rich in cellulose and low in lignin content. Similarly, *Pleurotus* spp. are best cultivated on paddy/wheat straws, hardwood sawdust, cottonseed hulls, and corn cobs. Wheat straw supports optimal growth of *Agaricus*. Furthermore, substrate formulations influence the biological efficiency and biological properties of the mushrooms and substrate, respectively. Differences in substrate formulation may lead to

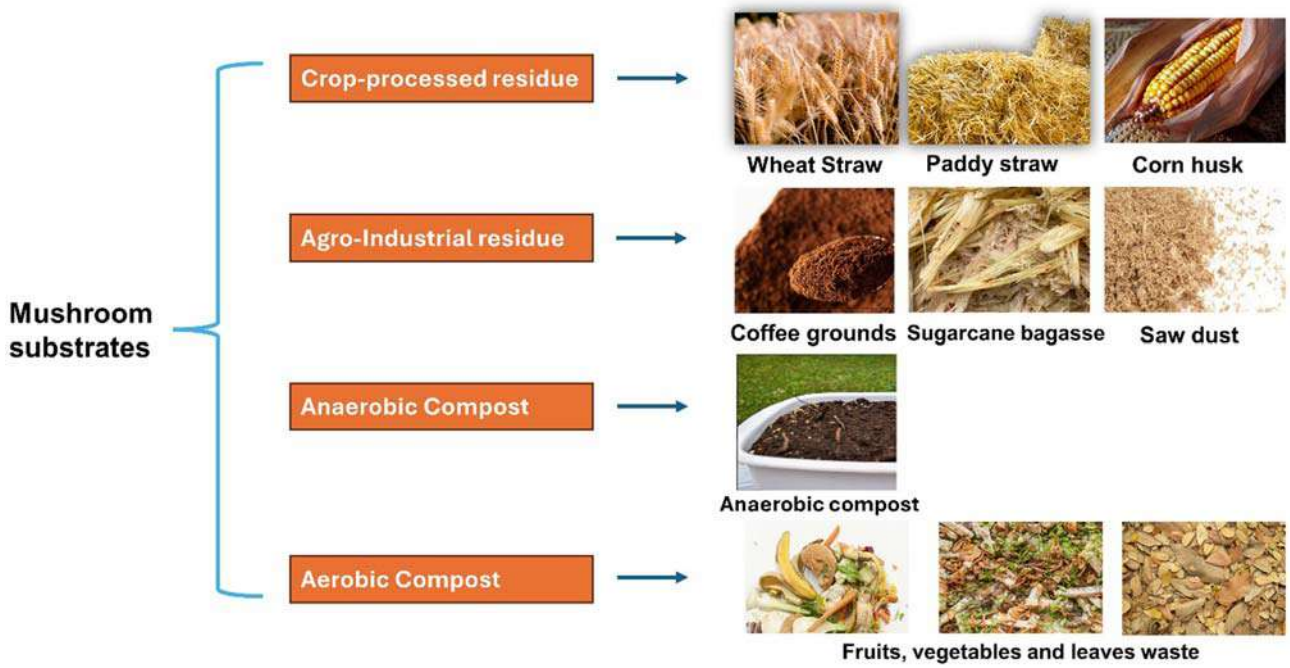


FIGURE 25.6 **Sources of mushroom substrates.** Common mushroom substrates from agro-industrial wastes are highlighted.

the establishment of different communities of microorganisms. The mushroom yields depend on the carbon-to-nitrogen ratio of the compost/substrate. Most mushroom substrates have low nitrogen content and are high in carbohydrates, primarily made up of cellulose, hemicellulose, and lignin. Supplementation of substrate with organic or inorganic nitrogen source essentially balances the C/N ratio. The optimum C/N ratio varies between different mushroom species. For example, *A. bisporus* and *A. bitorquis* require an optimum C/N ratio of 19/1. Similarly, *L. edodes, G. lucidum,* and *V. volvacea* have a C/N ratio requirement of 30−35/1, 70−80/1, and 40−60/1, respectively. Depending on the species, *Pleurotus* requires C/N ratios ranging from 45 to 60/1. Furthermore, the addition of substrates with gypsum, Epsom salts, and limestone also benefits in optimal mycelial colonization and fruiting body formation (Suwannarach *et al.*, 2022).

25.3.3 Methods for mushroom cultivation

A method that could address the issues of environmental degradation, hunger, and global poverty at once is mushroom farming (Cardwell *et al.*, 2018). The cultivation of mushrooms is a direct method of disposing lignocellulosic waste materials by turning them into edible biomass, which is a practical and profitable solution.

25.3.3.1 Cultivation on non-composted substrates

Several mushroom types, such as *Auricularia* species, *Pleurotus* species, *Flammulina velutipes, Ganoderma lucidum, L. edodes,* and *V. volvacea*, are cultivated on non-composted substrates. After being prepared, sterilized, or pasteurized, the substrates can be used unaltered. The steps in substrate preparation and cultivation on non-composted materials are discussed in section 2.1.2. There can be substantial variations in the yields and biological efficiency values (from 36.8 to 52.4%) across various cultivation substrates (Raut, 2019). With a biological efficiency of 52.4%, kenaf stalks were determined to be the most cultivable. Furthermore, mushrooms grown on a variety of substrates, including sugarcane bagasse, sawdust, corn cobs, wheat straw, and rice straw, resulted in biological efficiency varying from 35.47 to 71.56% based on the substrate.

25.3.3.2 Cultivation on composted substrates

Typically, composting substrates are used to cultivate button and paddy straw mushrooms. Biodegradation of lignocellulosic waste products yields compost, a humus-containing medium rich in nutrients (Carrasco and Preston, 2020). The details of compost preparation are outlined in section 26.2.1.2. A significant factor influencing mushroom productivity is compost formulation. Some mushroom varieties require additional supplementation of ammonium salts, urea, calcium, and

bran. Straw, animal dung, and gypsum are the main ingredients of compost. *Agaricus* species are typically produced using wheat straw, while *Volvariella* species are produced using rice straw and cotton seed waste (Suwannarach *et al.*, 2022).

25.3.3.3 Enzymes involved in substrate utilization

The feasibility of mushroom cultivation is based on their ability to convert and utilize lignocellulosic biomasses (in agro-industrial wastes) by elaborating lignocellulolytic enzymes and utilizing the degraded products in fruiting body formation. The hydrolytic and oxidative enzymes in mushrooms facilitate the breakdown of lignocellulose. Hydrolytic enzymes (cellulases and hemicellulases) degrade polysaccharides, and oxidative enzymes (ligninases) catalyze the modification and degradative reactions of lignin (Kumla *et al.*, 2020).

Cellulose, the most abundant component of lignocellulose polymer, contains a lengthy chain of interconnected sugar units to create a robust structure. The presence of intra- and inter-chain hydrogen bonding networks contributes to the stability (Zoghlami and Paës, 2019). Cellulases include a heterogeneous group of enzymes that function harmoniously, exhibiting diverse oxidative, hydrolytic, and non-hydrolytic activities. The cellulose polymer is hydrolyzed into glucose monomers by three major types of cellulases acting sequentially, viz., endoglucanases (endo-1,4-β-glucanases), exoglucanases (exo-1,4-β-glucanases), and β-glucosidases (β-D-glucoside glucohydrolase) (Escuder-Rodríguez *et al.*, 2018). Endoglucanases hydrolyze cellulose by cleaving its internal glycosidic linkages at random, resulting in the release of different-length oligosaccharides. Conversely, exoglucanases produce di-, tri-, and tetra-saccharides by hydrolyzing the cellulose chains from either the reducing or non-reducing ends. Finally, β-glucosidase specifically targets the β-1-4 linkage (found in disaccharides-cellobiose), releasing individual glucose molecules (Legodi *et al.*, 2019).

Within the lignocellulosic biomass, hemicelluloses are the second most prevalent type of biopolymers (Holtzapple, 2003). Heterogeneous sugars such as pentoses, hexoses, hexuronic acids, and trace amounts of rhamnose and fucose make up the typical structural composition (Peng *et al.*, 2012). Xylan, the major component of hemicellulose, is cleaved into monosaccharides by a group of enzymes acting synergistically. Endo-xylanases cleave the xylan backbone randomly, producing xylo-oligosaccharides, while β-xylosidases further break down these xylo-oligosaccharides into xylose monomers (Basit et al., 2018).

Lignin is a highly branched polymer with rigid aromatic, amorphous, and hydrophobic chemistry. Catalyzing the lignin degradation reactions that release simpler products include lignin-modifying enzymes such as laccases, cellobiose dehydrogenases, manganese peroxidases, and lignin peroxidases (Dudhagara and Payal, 2023).

25.4 Innovations, smart farming technologies, and automated cultivation processes in mushroom cultivation

25.4.1 Vertical farming system

The ever-increasing urban population and rapidly diminishing arable land demand alternative cultivation methods to ensure food productivity and security. To address these issues, vertical farming employs the principle of "farm up rather than out." Vertical farming technology is employed in mushroom production to minimize the land area while maximizing productivity. Vertical farming offers a smart farming space-efficient strategy by creating vertical modules or racks for cultivation, optimizing space requirement while enhancing the yield. As most mushrooms prefer a dusky environment for optimal growth, mushroom producers have aptly practiced vertical farming. However, variations in light intensities greatly impact the yields (Nájera et al., 2022).

25.4.1.1 Influence of light on mushroom growth and development

The type and dosage of light are the key elements impacting mushroom development. While light is not a major requirement for mushroom growth, proper development and shape of caps and stipes depend on indirect light illumination. The light spectra for optimum growth vary between mushroom varieties and can range from complete darkness to partial light. LED lights are a popular option for indoor vertical cultivation because of their energy-efficient features, exact light intensities, and adjustable wavelengths. Some of the bright sides of LED include simulation of ideal daylight conditions required by mushroom primordia, providing more uniform coverage, and requiring less electricity, making it more suitable for vertical systems with multiple canopy levels. For instance, the red and blue LED spectrums mimicking sunlight have been utilized in stimulating fruiting body formation (Al Mamun *et al.*, 2021).

The influence of different-colored lights on spore germination indicated an increase in total spore germination of *Pleurotus ostreatus* with red light, while blue light suppressed the mycelial growth. The longer illumination hours or usage of higher-intensity fluorescent light resulted in the higher yield of *Pleurotus eryngii*. Similarly, illumination with red and

blue lights increased the weight of *Pleurotus ostreatus*. The spore germination and fruiting body formation of *L. edodes* using red and blue light resulted in improved results compared to green light (De Bonis *et al.*, 2024). Thus, optimizing lighting conditions for different mushroom species is apparently essential to promote better growth and yields. Vertical farming technology has been practiced at a mushroom farm in the middle of Chicago's derelict stockyards (Al-Kodmany, 2018).

25.4.2 Hydroponic mushroom farming

A soil-less technique called hydroponics uses mineral nutrient solutions in water to grow mushrooms. Several advantages of hydroponics include the elimination of infections caused by bacteria, fungi, and insects; being a low-maintenance, less labor-intensive method; less water consumption; and easy possibilities of controlling nutrient levels and pH balance, resulting in better yields and uniform produce. The application of hydroponics for mushroom cultivation represents an innovative advancement in mycology revolutionizing the mushroom business and contributes towards sustainable agriculture. With hydroponics, mushroom growers benefit improved sustainability, production, and profit (Kaur and Kapoor, 2023).

Hydroponic farming requires a carefully monitored controlled environment that congenially supports mushroom growth. The optimal conditions required are a temperature between 24 and 27°C supporting germination of the mycelium, while optimal growth happens at a range of 27-29°C. The humidity is maintained at 90% or below along with a contamination-free nutrient solution. For most mushroom species, pH of the nutrient solution ranging between 6.0 and 7.5 is ideal. A 12-hour illumination cycle with either LED or low-intensity fluorescent lights and a good ventilation system to maintain stable oxygen levels while regulating carbon dioxide buildup is found to encourage mushroom growth hydroponically (Kaur and Kapoor, 2023). The mushrooms cultivated using hydroponic farming include button (*Agaricus bisporus*) (Bechara *et al.*, 2006), oyster (*Pleurotus ostreatus*) (Soza *et al.*, 2018), shiitake (*L. edodes*), and lion's mane mushrooms (*Hericium erinaceus*) (Kaur and Kapoor, 2023).

25.4.2.1 Pros and cons of hydroponic mushroom farming

The use of a hydroponic system is beneficial in several aspects. Compared to conventional farming practices, the process uses about 90% less water, thus aiding in water conservation. The possibility of a vertical hydroponic system leads to efficient utilization of space. Additionally, year-round production that out-rules seasonal fluctuations, higher yields, and a need for less labor are among other major benefits. Particularly, extreme abiotically stressed locations can easily adapt the technology. However, the high initial cost of setup and limited cultivable mushroom varieties are the major downsides of the approach (Kaur and Kapoor, 2023).

25.4.3 Solar-powered cultivation systems

Mushroom cultivation driven by solar energy has been harnessed as a creative energy-saving strategy. Many initiatives making use of solar renewable energy technologies have shown remarkable outcomes.

Solar-power integrated mushroom growing system is an inventive strategy developed by ICAR-IIHR to reinforce low-cost entrepreneurship development at both rural and urban levels. The approach is advantageous of being cost-effective and enabling cultivation in the outdoor environment even in the odd seasons. The technology uses the creation of an outdoor mobile growth chamber equipped with a solar mounted power system that adapts the principle of evaporative cooling to achieve the required growth conditions. The growth chamber is compact and is covered with nylon mesh to facilitate aeration and prevent entry of insects. To preserve the humidity within the chamber, moist gunny bags are placed over the entire setup. Very fine misting is created inside using a misting diaphragm pump equipped with nozzles. For convenient movement and transportation, the complete setup is housed inside a mild steel frame with movable wheels. The top of the frame has the solar panels installed, and the bottom has a water tank and a misting pump. The growth chamber has proven potential in the cultivation of elm oyster and white oyster mushrooms with higher yields.

Yet another approach toward sustainable cultivation uses a solar energy-based system for heating up water needed for the pasteurization of straw material in oyster mushroom cultivation. The approach is efficient in attaining a temperature of 60-80°C, saving up to 1,500 units of electricity annually. Furthermore, by slightly altering the setup to link the solar system's output line to the geyser's input and employing a thermostat to control the temperature, the cost of electricity can significantly be reduced (Singh and Upadhyay, 2016). A similar solar-powered approach encompassed controlling the growth of straw mushrooms in the enclosed and regulated environment producing approximately 421.08 kWh/y of electricity and reached 50°C in the water heating system (Chaiwong *et al.*, 2022).

25.4.4 IoT-enabled automated systems/hybrid cultivation systems

With traditional mushroom growing techniques, it can be difficult to monitor and regulate critical cultivation parameters like temperature, humidity, and light exposure. A decline in yields and quality can be directly linked to suboptimal conditions and may even escalate susceptibility to pests and diseases. Technology has advanced to the point that the growing of mushrooms has real-time environmental monitoring and control, revolutionizing the procedures involved in cultivation. Integrating the Internet of Things (IoT) overcomes the limitations associated with conventional practices. With the inclusion of IoT sensors and data analytics, real-time monitoring and control over cultivation parameters are possible. Consequently, hybrid cultivation systems combining traditional outdoor cultivation with approaches for climate-controlled inside environments are made possible by the integration of IoT systems into traditional farming procedures (Rukhiran *et al.*, 2023).

With the integration of IoT technology and solar energy sources, mushroom growing could realize a substantial economic potential in environmental control management. Real-time monitoring profitably benefits farmers in enhancing the yield and quality, boosting their economic viability, allowing them to effectively compete in the market and create new revenue streams. Moreover, the use of cutting-edge IoT-enabled growing systems highlights the revolutionary potential of precision agriculture, introducing new resource management approaches while refining and stabilizing environmental conditions. There have been notable effects from IoT-enabled cultivation systems in monitoring and regulating several environmental factors of Indian mushroom production processes.

The temperature and humidity conditions of mushroom growing rooms were regulated using an IoT system, allowing farmers to monitor the conditions directly through a web page (Hendinata and Fikri, 2023). An IoT-based system for controlling and monitoring the environment in home-based farming enabled regulating a range of parameters within the cultivation chamber including light intensity, temperature, humidity, and soil moisture level via a mobile and web-based application. Additionally, video and images of the mushroom growth could be visualized online (Chong *et al.*, 2023). A low-cost, centralized IoT ecosystem was utilized to monitor oyster mushroom farming in real time. It included agro-eCommerce for easy trade, an agronomist advising system for support, and early disease diagnosis and treatment. The provision of automated system uplifted the total production rate by 49% compared to conventional methods. Additionally, cultivars were able to upload images of the disease to the IoT ecosystem and receive predictions of the infection along with recommendations, which helped in achieving accuracy in disease detection (Guragain, Shrestha, and Bajracharya, 2024). All these aspects uphold IoT-enabled automated systems as a preferable choice over traditional cultivating techniques for year-round mushroom production.

25.5 Agro-repurposing of spent mushroom substrate (SMS) in sustainable agronomic practices

Worldwide interest in mass cultivating mushrooms has been sparked by their high nutritional profile and health-promoting qualities. The cultivation process is an eco-friendly approach due to its substantial reliance on natural wastes originating from agriculture, brewery, poultry, and others to produce fruiting bodies that are an excellent natural reservoir of unique nutritional and medicinal attributes. “Spent mushroom substrate” (SMS) or “post mushroom substrate” is that obtained after the harvest of mushrooms and further extension becomes unremunerative. The SMS generation can raise concerns about environmental pollution including groundwater contamination and other forms of environmental damage if not handled properly. Every year, the mushroom industry frequently needs to dispose of several million tons of used composted mushroom waste. For every kg of mushrooms produced, about 5 kg of SMS is generated. Because of its high cation exchange capacity, slow mineralization rates, and rich nutritional quality, SMS functions as an organic matter and can be further exploited for diversified applications including plant and second mushroom crop production, animal husbandry, recovery of enzymes, bioactive compounds, etc. (Ashrafi *et al.*, 2017). Depending on the type of mushroom grown, SMS can have varying compositions and characteristics. Several management and repurposing strategies of SMS are discussed in the following sections.

25.5.1 Reusing SMS for the cultivation of the second mushroom crop

After mushrooms are harvested, SMS is largely composed of used compost that is not further remunerated (Martín *et al.*, 2023) and can be reused in producing a second crop by its incorporation as bases of new substrates. Various factors considered for SMS utilization in second crop substrate preparation include substrate enrichment, substrate combination, and treatments applied. Reducing manufacturing costs and environmental impact can be achieved by integrating SMS effectively through innovative formulations and procedures.

The SMS of *A. bisporus* is reused in the second crop cultivation of *Agaricus* after autoclaving and supplementation with cottonseed and soybean meals. Similarly, for the cultivation of *Volvariella,* SMS from *Agaricus bisporus* and *Agaricus subrufescens* is reused with composted wheat straw and poultry manure. *Pleurotus* spp. SMS finds valorization in the cultivation of *P. ostreatus*, *P. florida*, and *A. blazei*. For the use of *P. ostreatus* SMS as the new substrate, the SMS is subjected to heat treatment followed by neutralization with calcium carbonate. Further, the formulation is added with a structural agent, gypsum, mixed well, moistened, and pasteurized before using as a new substrate. Shiitake (*L. edodes*) spent substrate is recycled to produce *Pleurotus* spp., *Ganoderma lucidum, P. sajor-caju,* and *Agaricus* (Zied *et al.*, 2020). Wheat bran, ground soybean, and white millet were included as supplements. Compared to traditional methods, mushrooms grown using SMS demonstrated higher yields and reduced production costs. The use of SMS as a substrate has proven to be an effective and efficient way to cultivate various edible mushroom species, offering a sustainable and cost-effective solution (North American Mycological Association, 2024).

25.5.2 SMS as casing material

The casing is a crucial factor that the yield of mushrooms involved in the agronomic procedure depends on. Casing involves application of soil-compost mixture as a layer to the open surface of a fully spawned mushroom, which provides the necessary factors for the growth and development of fruiting bodies, including physical support (Sharma, Sharma, and Gurjar, 2021). Casing typically provides moisture, gaseous exchange, anchorage, and vital reserves for the developing mushroom sporophores. The presence of a high amount of nutrients facilitates SMS to be incorporated as a casing material. However, SMS should be subjected to various treatments prior to being used as a casing material, which includes thermal treatment (for preventing pests and diseases out of the cultivation chambers and compost), maturation, and washing. The use of aerobically fermented SMS as casing provided comparable yields with peat-based casing material. Mushrooms successfully grown using SMS as a casing material include oyster, shiitake, and lion's mane mushrooms.

25.5.3 SMS application as a soil conditioner and bio-fertilizer

SMS has also been utilized in the agricultural sector for improving the soil health and overall development of crop plants (Zakaria, Boopathy, and Dib, 2020). The beneficial roles of SMS application in agriculture are witnessed as (1) improvements in soil quality, (2) adsorption of organic and inorganic pollutants, (3) serving as a good carrier for the plant growth promoting microbes (PGPM), and (4) showing the best biological efficiency against soil and plant pathogens (Economou, Diamantopoulou, and Philippoussis, 2017). Spent materials usually have a high concentration of salts and nitrates. Hence, used substrates are either weathered or leached, for consideration as a good source of organic matter, rich in macro- and microelements, and to increase the soil's biological activity.

The use of SMS for maize crops increased maize germination, height, stem diameter, shoot fresh and dry masses, and leaf area with increased leaf P, K, and S levels and K content in the soil (N.M. Ngan and Riddech, 2021). SMS as an organic amendment and carrier for *Bacillus amyloliquefaciens* inoculants significantly improved the plant growth and chlorophyll content in *Hibiscus sabdariffa* (N.M. Ngan and Riddech, 2021). Through regulating microbial populations and stimulating rhizosphere soil microbial activity, the combinatorial application of PGPR and SMS improved crop production and plant growth in tomato continuous cropping soil (Wang *et al.*, 2022; Khalil *et al.*, 2024). Bacterial isolates from spent substrates based on their enzymatic functions (phosphatase, xylanase, protease, and cellulase activities), *Pseudomonas* species predominated in the spent mushroom compost (SMC) and *Bacillus* in the spent oyster substrate (SOS) (Khalil *et al.*, 2024).

25.5.4 Use of SMS in plant-disease management

The rich organic content of SMS supports the growth of diverse categories of microorganisms including those that exhibit antagonistic activity against plant pathogens (Zied *et al.*, 2020). SMS harbor bacterial communities such as *Pseudomonas* and *Bacillus* sp., which suppress the growth of pathogens. *Bacillus subtilis, Bacillus licheniformis,* and *Bacillus amyloliquefaciens* from SMS extract, demonstrated antagonism against *Lecanicillium fungicola,* that causes dry bubble disease of white button mushroom. Besides, *Pseudomonas aeruginosa* isolated from re-composted SMS inhibited the growth of plant pathogens: *Pyricularia, Rhizoctonia solani, Sclerotinia,* and *Fusarium* (Borrero *et al.*, 2013). Khalil et al. reported SMC and SOS to harbor bacterial strains with suppressive activities against *Botrytis cinerea, Phytophthora* sp., *Rhizoctonia solani* (on fruits), and *Alternaria alternata* (on root), which commonly appear in horticultural production systems (Khalil *et al.*, 2024).

25.5.5 Influence of SMS on nutritional value and secondary metabolites production in plants

Secondary plant metabolites play a crucial role in the survival and adaptation of plants within their environment and have remarkable therapeutic potential for human health (Martín *et al.*, 2023). The application of SMS enhanced the nutritional value and secondary metabolites in various plants. Growth media added with 10-15% SMS increased the essential oil concentrations in German chamomile flowers (Vahid Afagh *et al.*, 2019). Similarly, the use of oyster and button mushrooms SMS as growing media caused elevations in protein and carotenoid levels in *Capsicum annuum* fruits (Roy *et al.*, 2015). SMS from shiitake and oyster mushrooms demonstrated antimicrobial and antioxidant properties, indicating bioactive compounds' positive impact on plant growth and development (Zakaria, Boopathy, and Dib, 2020). Further, a combined effect of SMS and inorganic fertilizer assessed on tomato plants indicated an improvement in total protein, vitamin C content, and yield compared to using only inorganic fertilizer, suggesting SMS as a bio-stimulant, improving both the nutritional and phytochemical profiles in plants (Ashrafi *et al.*, 2016). Bio-enrichment of soil with earthworm-fed SMS and *Trichoderma harzianum* elevated the overall phenolic, mineral content, antioxidant capacity, and flavonoid levels in mature tomato fruit (Singh *et al.*, 2018). Utilizing SMS as a growth medium or soil amendment to boost the phytochemical and nutritional profile of different plant species presents a sustainable way to increase the quality of agricultural output (Sun and Shahrajabian, 2023). However, further research elucidating the mechanisms of primary and secondary metabolites accumulation by SMS supplementation in plants can be more beneficial.

25.5.6 Other applications of SMS valorization

Several other effective valorization applications of SMS include vermicomposting, animal feed, soil amendments, and fertilizers. Additionally, SMS has also been used to produce bioethanol, biogas, bio-hydrogen, bio-oil, solid biofuels, and volatile fatty acids (VFAs). Further, SMS and SMC are also utilized in environmental pollution control in bioremediating the contaminated soils with dyes, heavy metals, PAHs, pesticides, and emerging contaminants thus improving soil health and aiding in land reclamation and revegetation (Leong *et al.*, 2022).

25.5.6.1 SMS as feed

The use of SMS as feed is a cost-effective alternative to support nutrition and well-being in animals. SMS contains abundant fibers and fungal mycelium rich in protein, potentially boosting animal health by enhancing antioxidant capacity and fat metabolism (Chuang *et al.*, 2020). SMS from *Flammulina velutipes* demonstrated serum cholesterol lowering potential and enhanced immunomodulation in broilers. Similarly, SMS from *Pleurotus eryngii* remarkably lowered lipid peroxidation and improved meat quality in broilers (Lee *et al.*, 2012). Feeding broilers with *Cordyceps militaris* SMS decreased blood lipid levels (Noopan, Chanjula, and Wattanasit, 2019). Hanwoo steers fed with microbially fermented SMS significantly improved the growth performance and carcass traits. *Pleurotus* SMS has been evaluated as feedstock for goats, lambs, and sheep. Furthermore, *L. edodes* spent substrate assisted in ruminant digestion (Rinker, 2017; Martín *et al.*, 2023; Azman *et al.*, 2023).

25.5.6.2 SMS in the recovery of enzymes and bioactive compounds

The waste mushroom bed extracts are exploited for the production of bioactives and industrial enzymes as a cost-effective approach (Nidadavolu *et al.*, 2012). A significant extraction of laccase from the *Pleurotus* SMS was achieved through solid-state fermentation, facilitating a cost-efficient ligninolytic enzyme isolation. Phenolic compounds, carbohydrates, and sterols were identified in the extracts of *Pleurotus* (Klausen *et al.*, 2023). Good yields of ethanol, phenolic compounds, acetic acid, and xylose were extracted from Shiitake SMS hydrolysates (Chen *et al.*, 2022).

25.5.6.2.1 Mycoremediation of agricultural/agro-industrial wastes: A strategy using mushroom cultivation. Besides the nutritional and medicinal values, mushrooms also find applications in the development of "clean technologies" , such as mycoremediation, which involves approaches utilizing fungi and mushrooms for the removal of environmental pollutants. Mushrooms as mycoremediants decontaminate pollutants and stimulate the environment by several processes, including (1) biodegradation, (2) biosorption, and (3) bioconversion (Figure 25.7).

25.5.6.2.2 Mushrooms in biodegradation. Biodegradation is a microbial-mediated process of recycling wastes, breaking down organic materials into nutrients. Complex chemical molecules completely mineralize during the biodegradation process to produce simpler forms like CO_2, NO_3, H_2O, and other inorganic compounds (Barh *et al.*, 2019). Biodegradation is one of the eco-friendly methods of removing toxic and dangerous substances persisting in the

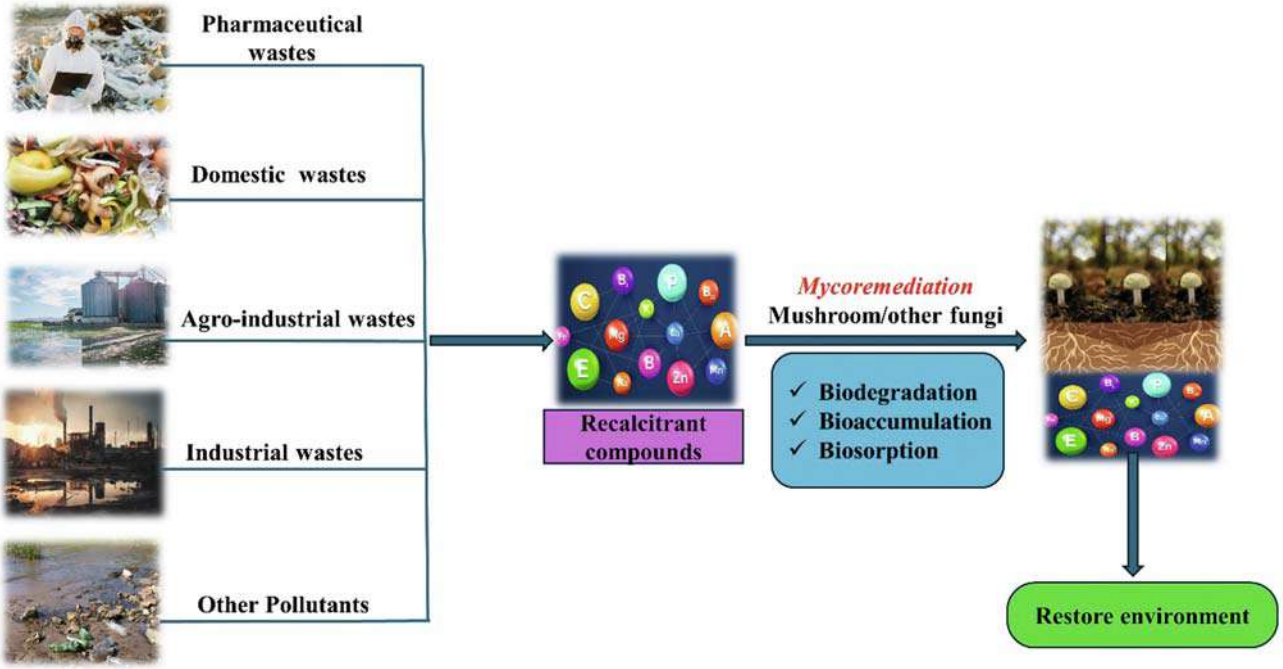


FIGURE 25.7 **Mycoremediation of agro-industrial wastes by mushrooms.** Figure illustrates different mycoremediation processes carried out by mushrooms.

environment. In the process, various types of wastes including weeds and straw from fields, animal feces and dead remains from livestock, and molasses and peels from agro-industrial waste materials are decomposed by mushrooms and are ultimately reduced and recycled for enhancing their usability. The implication of these macrofungi in biodegradation is based on their ability to secrete extracellular enzymes typically induced by their substrates that can oxidize recalcitrant pollutants (Nyanhongo *et al.*, 2007). The enzymes from mushrooms are efficient in degrading nonpolymeric, intractable pollutants such as organic and synthetic dyes, nitrotoluenes, polycyclic aromatic hydrocarbons (PAHs), pentachlorophenol (PCP), and polymers such as plastics (Table 25.3).

25.5.6.2.3 Mushrooms in biosorption. Biosorption is an approach by which mushrooms extract metals, contaminants, and xenobiotics from wastewater (Barh *et al.*, 2019) and is a proficient way to remediate and recover metals from industrial wastes. In comparison to other organisms including plants, mushrooms have acquired more adaptability and high metal accumulation mechanisms (Yadav *et al.*, 2021). The two major mechanisms by which mushrooms enhance the absorption of these contaminants are (1) bioaccumulation and (2) biosorption (Barh *et al.*, 2019). *Bioaccumulation* is an active metabolism-dependent process to accumulate and concentrate heavy metals by cellular transport and partitioning into intracellular components. Mushrooms, in response to metal stress, release stress-related factors such as metallothionein, glutathione, and plastocyanin, which are proteinous and non-proteinous compounds facilitating metal ion uptake (Damodaran, Vidya Shetty, and Raj Mohan, 2014). Intracellular accumulation is aided through cell membrane transport mechanisms such as active transport, facilitated diffusion, and passive diffusion (Yadav *et al.*, 2021). *Biosorption* is based on the ability of the biomass to bind pollutants. Based on the cell metabolism, the absorption mechanism is categorized into (1) metabolism-independent biosorption and (2) metabolism-dependent biosorption. The sorption process independent of metabolism is relatively faster, reversible, and operates without the expense of metabolic energy for binding metal/pollutants to the biomass. The biosorption process facilitated by ion exchange, adsorption, and covalent binding interactions facilitates the biosorption process. The presence of polar groups in proteins, amino acids, lipids, and structural polysaccharides brings about efficient binding interactions in the processes. The biosorption processes can be achieved both through dead and live biomass. However, dead biomass of mushrooms more advantageously carries out biosorption processes over live biomass. The dead mushroom biomass is insensitive to toxicant/pollutant concentrations and their toxicity effects and is least affected by metal ion concentration, temperature, nutrients, pH, etc., unlike living mushroom biomass. Despite the advancements in mycoremediation through mushrooms, their insufficiency for human consumption is still a limitation. Several studies reported the accumulation of high concentrations of heavy metals and mutagenicity in the

TABLE 25.3 **Biodegradation by mushrooms and enzymes involved.**

Mushroom species	Agro-industrial waste/ pollutants	Biodegrading enzymes	References
Agricultural/domestic waste degradation			
Pleurotustuber-regium	Cotton waste Rice straw	Lipase, Peroxidase, Cellulase carboxymethylcellulose enzymes	(Suwannarach et al., 2022)
Volvariella volvacea	Banana leaves	Lignocellulosic and hydrolytic enzymes	
V. volvacea	Sawdust	Lignocellulosic enzyme	(Suwannarach *et al.*, 2022)
Pleurotus sapidus	Wheat straw Rice straw Corn stover Corn cobs Sugarcane bagasse (SCB) Banana stalk (BS)	Ligninolytic and cellulolytic enzymes	
Industrial chemicals/dye waste degradation			
Pleurotus ostreatus	Remazol Brilliant Blue R	Manganese peroxidase Manganese independent Peroxidase and phenol oxidase	(Suwannarach *et al.*, 2022)
Ganoderma sp.	Textile effluents	Laccases	
Pleurotus pulmonarius BPSM10	Malachite green	Laccase	(Dias, Zied, and Pardo-Gimenez, 2021)
Lentinus edodes	Poly-478 and Remazol Brilliant Blue	Manganese peroxidase	(Singh et al., 2018)
Pleurotus ostreatus	Synthetic dye	Laccases, lignin peroxidases	(Sakamoto, 2018)
Lasiodiplodia sp.	Malachite green	Laccase	(Sakamoto, 2018)
Industrial pollutants/waste degradation			
Pleurotus ostreatus	Plastics, green polyethylene	Lignocellulolytic and laccase enzyme	(Kumla et al., 2020)
Pleurotus pulmonarius	Crude oil	Peroxidase	(Pérez et al., 2002)
Phanerochaete chrysosporium	DDT, PHAs, PCBs	Lip, MnP	(Pérez et al., 2002)
Lentinula edodes	2,4-Dichlorophenol	Ligninolytic enzyme	(Suwannarach et al., 2022)
P. chrysosporium	Styrene	Peroxidases	
Pleurotus pulmonarius	Radioactive waste	Ligninolytic enzyme	

fruiting bodies that are grown on contaminated substrates due to the process of absorption (Golian *et al.*, 2022; Demirbaş, 2001) (Table 25.4).

25.5.6.2.4 Mushrooms in bioconversion. Mushrooms are essential players in the bioconversion by converting lignocellulosic waste into products having additional value. Waste materials from industry or agriculture that are no longer useful can be bio-converted into useful products with excellent organoleptic qualities (Yadav *et al.*, 2021). Consequently, the key result of bioconversion reaction is the fruiting bodies of mushrooms. The process of bioconversion largely depends on the composition of organic wastes. Several agro-industrial lignocellulosic wastes utilized successfully in cultivation

include paper, tea waste, millet/rice/wheat/barley/oat straw, spent coffee grounds, vegetable and fruit seeds and peels, and food waste digestate. The lignocellulolytic enzymes catalyzing bioconversions are peroxidases and oxidases. Peroxidases form free radicals and reactive ions that cause destruction of lignin and humic substances. Laccases and tyrosinases having copper-containing active sites are phenol oxidases efficiently involved in biocatalysis, produced by the genera of *Agaricus* and *Pleurotus*. Furthermore, the cultivated mushrooms promote the biotransformation of agricultural biomass into useful products such as proteins, carbohydrates, enzymes, and different kinds of secondary metabolites (Malik *et al.*, 2021) (Table 25.5).

TABLE 25.4 Mushrooms involved in biosorption of metals/other pollutants.

Mushroom species	Biosorption process	References
Biosorption of different dyes by mushroom		
Agaricus bisporus	Basic Red 18, Levafix Braun E-RN, Acid Red 11, Crystal Violet, and Brilliant Blue Green	(Chaudhary et al., 2023)
Pleurotus ostreatus	Malachite green, xylidine, and methylene blue	(Suwannarach *et al.*, 2022)
Lentinus edodes	Poly-478 and Remazol Brilliant Blue R	
Ganoderma sp.	Textile effluents	
Pleurotus pulmonarius	Remazol Brilliant Blue R, Congo red, methylene blue, and ethyl violet	
Biosorption of heavy metals by mushroom		
Agaricus macrosporus	Cd, Hg, Cu, Zn, Pb, Cr, Cd	(Usman, Murtaza, and Nutritional, 2021)
Pleurotus ostreatus	Cadmium	(Patel and Trivedi, 2016)
Agaricus bisporus, Lactarius piperatus	Cd II ions	(Nagy et al., 2014)
Ganoderma lucidum, Volvariella volvacea, Coriolopsis strumosa, Daedalea tenuis, Lenzites malacanis, Phellinus xeranticus, Trametes lactenia	Cd, Pb, Co, Cu II, Cu	(Suwannarach et al., 2022)
A. bisporus, Calocybe indica, Pleurotus platypus	Cu, zinc, iron, cadmium, nickel, lead	

TABLE 25.5 Enzymes elaborated by mushrooms in bioconversion of agro-industrial wastes.

Agro-industrial waste	Lignocellulosic enzymes
Banana leaves Cotton waste Rice straw	Lipase Peroxidase Cellulase Carboxy methylcellulose enzyme
Eucalyptus waste	Lignocellulosic enzymes
Sawdust	Lignocellulosic enzymes
Wheat straw Rice straw Corn stover Corncobs Sugarcane bagasse (SCB) Banana stalk (BS)	Ligninolytic and cellulolytic enzymes
Ramie stalk Textile waste	Ligninolytic and cellulolytic enzymes
Wheat straw	Lignocellulosic enzymes

Adapted from Suwannarach *et al.* (2022).

25.6 Conclusions

Being rich reservoirs of nutritional and therapeutic molecules, mushrooms have attracted special attention as functional foods among people resulting in a spike in domestic and commercial production. Mushroom farming technology is a cost-effective, efficient way of valorizing agricultural wastes into profitable production of fruiting bodies. The gradual transition from conventional to highly advanced technologies in cultivation techniques has significantly improved yields, allowing for cultivars with higher financial returns. Furthermore, the use of spent mushroom waste for a variety of agronomic techniques and mycoremediation tools has provided a sustainable solution for the long-term cultivation of these macrofungi.

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Part V

Regulatory and policy frameworks for sustainable waste management

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Chapter 26

Policies and strategies to promote sustainable agricultural waste management practices

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Chapter Outline

26.1. Introduction **467**
26.2. Strategies for promoting sustainable agricultural waste management 468
26.3. Approaches for integrated waste management 470
26.4. Case studies and best practices 472
26.5. Policies and regulatory framework 472
26.6. Conclusion 474
References **474**

26.1 Introduction

Agriculture holds an important place in human civilization as it serves as the livelihood of billions of people. Globally, an abundant quantity of agricultural waste is generated every day and every year to fulfill the increasing demand of the ever-growing population. The significant rise in the production of crops and livestock typically contributed to the generation of agricultural wastes. However, its substantial amount and improper waste management practices have become a daunting problem for human health, food security and environment (Koul, Yakoob, and Shah, 2022).

Agricultural wastes can be defined as the byproducts or material residues of the production and processing of agricultural products such as vegetables, fruits, livestock, dairy products, poultry, and crops. It falls under no-product value outputs and may possess materials useful to humans. They may be present in various forms such as solid, liquid, gas, or slurry, and their composition varies depending on the type of agricultural activity and operations conducted. This agro-waste can be generated from varying sources such as animal residues, food industry wastes, crop residues, and aquaculture waste, as well as toxic and dangerous agricultural waste from herbicides, insecticides, or pesticides.

The utilization of agricultural waste requires careful and proper management practices, as its improper disposal and if not properly utilized may negatively impact the ecosystem, leading to nutrient imbalance, soil and water contamination, air pollution, and even global warming. Pollution and habitat alteration can adversely affect wildlife and humans. Thus,

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agricultural waste management is a crucial aspect of sustainable agriculture, involving the proper handling, treatment, and disposal of waste generated by farming activities. It emphasizes the systematic and organized use of agricultural byproducts through sustainable methods that preserve and enhance the quality of air, water, soil, and plant and animal resources. Such management practices can turn waste into value-added products such as organic fertilizers or green energy such as biogas.

Recently, agricultural waste management is become an issue of concern to policy makers around the world. Some of the best practices in waste management include providing incentives for adopting environmentally friendly waste management techniques, ensuring that agricultural operations adhere to waste management standards, and raising awareness among farmers, agriculture businesses, and communities on the negative impacts of excess waste and how to reduce waste by promoting single-use plastic and eco-friendly product designs. Governments and international bodies are also establishing various regulations and guidelines to promote sustainable agricultural waste management (Murova, 2022).

The primary goal of sustainable agricultural waste management is to promote sustainable agriculture, reduce waste, minimize costs, ensure compliance, protect the environment, and ensure food security (Duque-Acevedo *et al.*, 2022). Effective waste management in the agricultural world is not just an afterthought; it is a necessity. It allows the conversion of agricultural wastes into valuable products, which not only enhances the marketability of agricultural products but also meets consumer demand for eco-friendly and sustainably produced goods. Adopting sustainable practices like composting and biochar application enhances soil health and prevents nutrient runoff and contamination of water bodies, thus safeguarding aquatic ecosystems.

Modern sustainable waste management techniques such as converting waste to energy, special waste disposal, and recycling and reusing agricultural byproducts help minimize waste, enhance resource efficiency, and mitigate the adverse health and environmental impacts, including the spread of communicable diseases, air and water pollution, land degradation, emissions of methane and hazardous leachate, and climate change (Abubakar *et al.*, 2022). It also promotes economic viability with the utilization of waste as a resource for producing bio-fertilizers or animal feed, which lowers production costs for farmers and can create new job opportunities in the recycling, composting, and renewable energy sectors. Adopting sustainable waste management practices helps farmers comply with environmental regulations and standards and ensures the long-term sustainability of farming practices.

26.2 Strategies for promoting sustainable agricultural waste management

26.2.1 Overview of emerging innovative technologies for managing agriculture waste

Due to the diverse sources of agricultural waste, their sustainable management requires appropriate and innovative approaches at various stages of the process, from the collection of the waste to its disposal, for sustainable agriculture and environmental protection. Some of the emerging innovative technologies that can be explored and implemented are categorized below.

26.2.1.1 Biochar production

Biochar is a type of charcoal produced from organic waste through various processes such as torrefaction, combustion, gasification, and slow and fast pyrolysis. Among these, pyrolysis is a more reliable and cost-effective technique to produce biochar. In this process, slow pyrolysis produces a higher biochar yield than fast pyrolysis. The production of good-quality biochar often requires efficient kilns or retorts and a complex manufacturing process, including the removal of moisture from raw materials through pyrolysis of biomass in a retort using appropriate technology but at low cost (Wijitkosum, 2022).

Microwave-assisted pyrolysis (MAP) is one of the most promising and novel approaches for biochar production. It uses volumetric heating, where the heating mechanism is applied from the core to the outer part of the material to convert the agricultural biomass waste into biochar (Rex *et al.*, 2023). It is faster, highly efficient, selective, controlled, and adaptable in comparison to traditional approaches to heating pyrolysis. In agriculture, the use of biochar has been proven to improve soil fertility, retain water, and sequester carbon, making it a valuable agricultural amendment. The use of biochar in agriculture can help mitigate global warming by absorbing carbon from the atmosphere and lowering greenhouse gas emissions from the soil. Crop waste is managed and hazardous gas emissions are decreased when agricultural crop residues

are turned into biochar. The production of biochar from agricultural waste and its application as soil amendment helps produce extremely fertile soil that doesn't require chemical stabilization (Patel and Panwar, 2023).

26.2.1.2 Anaerobic digestion (Biogas)

Producing biogas from agri-waste, a renewable energy source, is one of the safest, cleanest, and most cost-effective ways to generate energy and one of the best alternatives for petroleum derived products. The process of anaerobic digestion involves the breaking down of organic materials in an oxygen-free environment to produce biogas, a mixture of methane and carbon dioxide, and digestate, a nutrient-rich fertilizer. Biogas can be produced from various sources such as agro-industrial wastes with lignin, cellulose and hemicellulose, livestock manure, household wastes, sewage, energy crops, and crop residues with sugarcane straws, rice straws, fallen leaves, wheat straw, stover, and so on.

Animal dung is utilized mostly in the production of biogas, followed by industrial and agricultural wastes through anaerobic digestion, a recycling method. Among many of these sources, sugarcane straw proved to be a more promising source, producing about 94% of the biogas and reducing greenhouse gas emission levels (Keerthana Devi *et al.*, 2022). Biogas production from the anaerobic digestion of agricultural waste and residue represents an environmentally and economically feasible technology for the conservation of renewable energy resources in a sustainable manner (Chitara *et al.*, 2021). Biogas has emerged as a highly effective waste management technique, especially in developing countries.

26.2.1.3 Precision agriculture technology

Precision agriculture technologie are transforming the agricultural industry by increasing productivity, efficiency, and sustainability. Technologies such as GPS-guided tractors, remote sensing, drones, IoT (Internet of Things) devices, data analytics enable farmers to monitor and manage crops more effectively with unprecedented accuracy. This can help reduce the overuse of fertilizers and pesticides, thereby minimizing agricultural waste, reduces environmental impact, and encourage sustainable farming practices (Getahun *et al.,* 2024) Agriculture 4.0, the fourth agricultural revolution, is driven by recent developments in cloud computing, IoT, and technologies like robotics and big data. Agriculture 4.0 maximizes production, supply chain, and logistics performance in an ethical way by utilizing modern technologies for real-time data processing, analysis, and decision-making. By reducing food losses and waste and enhancing food security, Agriculture 4.0 seeks to make agrifood systems more sustainable (Bahn *et al.,* 2021). Furthermore, integrated pest management (IPM) techniques encourage the sustainable use of pesticides, minimizing toxic chemical waste and reducing the risk of environmental contamination (Deguine *et al.*, 2021).

26.2.1.4 Biological methods (Compositing)

In the agriculture sector, agro-waste is typically burned in massive amounts, causing environmental pollution. Instead, it can be converted into compost or bio-fertilizers by using microbes and enzymes to break down the highly biodegradable organic waste under aerobic conditions into stabilized organic matter. This process usually takes 90 days but can be accelerated based on the multitude of microorganisms (bacteria) and enzymes present that can help in rapid decomposition. This approach reduces landfill waste and solid waste disposal costs and provides sustainable soil amendments.

Recently, on-farm composting technology has emerged as an innovative approach with more environmental benefits. It allows the recycling of in situ residual biomass into high-value-added products for soil amendment and plant nutrition (De Corato, 2020). In comparison to landfilling and anaerobic digestion, it reduces greenhouse gas emissions and leachate generation.

26.2.1.5 Waste-to-energy technologies

Technologies that convert agricultural waste into energy include biomass boilers and thermochemical conversion processes (torrefaction, pyrolysis, gasification, liquefaction and combustion). These processes utilize crop and plant residues, micro- and macroalgae, and other biomass wastes, leading to the production of an eco-friendly energy source, that is, solid, liquid, and/or gaseous biofuels. Biofuel production can provide various renewable energy sources, such as the production of biochar, charcoal, biohydrogen, bioethanol, biomethane, bio-oil, syngas (gaseous biofuels), and biobutanol, thus offering multiple environmental benefits over fossil fuels, including waste reduction.

Moreover, researchers and scientists have developed a novel technology for using genetic engineering in biofuel production. As biofuel production entirely depends on feedstock productivity and biomass efficiency, many studies have observed significant improvements in achieving these goals, either by the suppression or elimination of the expression of various genes, related to biosynthesis through genetic engineering (Ambaye *et al.*, 2021).

26.2.1.6 Blockchain and traceability

The traceability of food safety information is no longer guaranteed by the conventional agricultural food logistics and transportation model, therefore it is crucial to set up an efficient traceability system. Implementing blockchain technology for traceability in agricultural supply chains can help reduce waste by optimizing logistics, minimizing losses during transportation, and improving inventory management. Customers can check the product's production details, processing method, shipping route, and other details by scanning the QR code on the goods or visiting the website thanks to blockchain traceability, which also helps them to understand the product's authenticity, quality, and safety. However, more research and an in-depth understanding of the underlying technology, which is subject to many restrictions, delay time, capacity, and security, are still required (Lv *et al.*, 2023).

26.2.1.7 Biorefineries technology

Green bio-based refineries (biorefineries) utilizing lignin-cellulosic and oleaginous feedstocks could significantly shift global perspectives by converting larger amounts of disposable agricultural biomass into a diverse range of high-value co-products and byproducts of various farm purposes (De Corato *et al.*, 2018). For example, it can be used in the production of bio-based chemicals which are generally used in basic platforms (e.g., cellulose, hemicellulose, lignin, furfural, amino acids, peptides, proteins, xylose, succinic acid, lactic acid, citric acid, 1,3-propanediol, lysine, glutamic acid), high-value products in advanced farming systems (e.g., soil amendments, phytosanitary drugs, plant bio-stimulants, and biofertilizers), and high-value products in biomaterial industries, including bioplastics, lignin, and alginate (Table 26.1).

26.2.1.8 Smart waste disposal technology and artificial intelligence (AI)

Technology based on smart collection systems to advanced sorting processes is one of the emerging innovative strategies for effective waste management (Mashudi *et al.*, 2023). Through the use of sensors and IoT technology, one can increase waste disposal efficiency by optimizing schedules, water usage, and resource allocation, thereby reducing waste and cost. On the other hand, this technology, in combination with pyrolysis and other revolutionary processing methods, can convert waste into alternate energy sources or high-value products, reducing the environmental impact by reducing dependence on fossil fuels. For example, a city implemented a smart collection system that successfully reduced the frequency of empty waste hauls, optimized the collection routes, helps in adjusting waste collection schedule and demand prediction (Idrissi *et al.*, 2024).

26.2.1.9 Circular economy approaches

Morseletto (2020) refined the concept of circular economy as an "economic model aimed at the efficient use of resources through waste minimization, long-term value retention, reduction of primary resources, and closed loops of products, product parts, and materials within the boundaries of environmental protection and socioeconomic benefits." Promoting the concept of reuse, recycling, and repurposing agricultural waste products can minimize generation and create economic opportunities within local communities. Such approaches include narrowing resource loops, slowing resource loops, closing resource loops, and regenerating resource flows (Velasco-Muñoz *et al.*, 2021).

Apart from this, agricultural wastes have been widely used in the production of supplementary animal feeds, roof thatching, mulching, fibers for the textile industry, paper making, construction, and mushroom cultivation (Table 26.1). The technologies explained above represent a diverse range of approaches that address agricultural waste management challenges while promoting sustainable practices in agriculture.

26.3 Approaches for integrated waste management

Integrated waste management (IWM) involves the strategic use of a variety of waste management practices to handle waste in a way that covers all the sources and aspects covering collection, segregation, transfer, sorting, treatment, recovery, and disposal in an integrated manner, which promote sustainability. One such approach that can generally be implemented is the collective management of all the agriculture waste sources with the use of 3Rs, that is, reduce, reuse, and recycle policies and strategies.

Developing comprehensive waste management plans that integrate various waste management practices, such as technologies related to waste and sludge treatment, is economical and eco-friendly and brings economic returns. They can be employed in developing countries where waste treatment methods, such as composting, anaerobic digestion, and recycling of plastic and agricultural waste in construction, can be used. One such approach is the development of

TABLE 26.1 **Sustainable utilization of agricultural wastes in various agricultural waste management strategies.**

Agricultural residues	Strategies	Result	References
Cassava, pineapple, plantain, banana, and yam peels, rice husks, rice bran, corn husks, corn cobs, palm kernel cake, soybean meal, wheat bran	Animal feed	Used as a nutrient source supplement for animals Minimize waste	(Yafetto, Odamtten, and Wiafe-Kwagyan, 2023)
Straw, palm leaves, and water reeds	Roof thatching	Produces water-resistant, lightweight, flexible, durable, and eco-friendly roof cover	(Koul, Yakoob, and Shah, 2022)
Straws, husks, grasses and cover crops, sawdust, compost, and manures	Surface mulching	Prevents soil erosion Conserve soil moisture Enhance soil nutrients Eliminates residual pesticides and fertilizers roves soil retention rate Prevents soil evaporation	(Iqbal *et al.*, 2020)
Rice straws, wheat straws, potato plants, and mustard stover	Composting	Reduces landfill waste Minimize waste disposal costs Provides sustainable soil amendments Reduces greenhouse gas emissions	(Waqas *et al.*, 2023)
Date palm residues, wheat and maize straw, wood, manure, rice husk, coppiced woodland	Biochar	Improves crop yields Promotes soil carbon sequestration Reduces greenhouse gas emissions Reduces fertilizers	(Patel and Panwar, 2023)
Sugar cane, animal dung, corn, sorghum, wheat, beetroot, citrus pulp, olive pomace	Biogas	Simple and cost-effective method Reduces carbon dioxide emissions	(Keerthana Devi *et al.*, 2022)
Rice straw maximizes sugarcane bagasse, oil cakes, banana peel, rice husk, sawdust, and wheat straw	Biofuel	Renewable energy source Biodegradable, low-cost, and eco-friendly method	(Awogbemi and Kallon, 2022)
Lignin-cellulosic and oleaginous feedstocks	Biorefineries	Produces high-value bio-based chemicals, bio-fertilizer phytosanitary drugs, plant biostimulants, etc. Reduces waste	(De Corato *et al.*, 2018)
Rice straw, wheat straw, corn cobs, sawdust and rice husk, and sugarcane bagasse	Mushroom cultivation	Cost-effective practice of mushroom production Mitigate the issue of malnutrition and environmental pollution	(Akter *et al.*, 2022)
Rice husk ash, sugarcane bagasse ash, wheat, barley straws, and bamboo leaves	Construction	Develop effective and eco-friendly sustainable construction materials such as bricks, green concrete, reinforcement materials, and bio-based plastics Thermal and static qualities	(Maraveas, 2020)
Corn stalks, sugarcane bagasse, wheat and rice straw, cotton stalks	Paper and pulp industry	Used in paper and pulp production Promising alternatives to woody materials Mitigates the issue of deforestation, greenhouse gas emissions, and global warming	(Worku *et al.*, 2023)
Oil palm, bagasse, corn stalks, coir, bamboo, pineapple, banana, and rice husk	Fibers	Used as an alternative to wood for making furniture	(Koul, Yakoob and Shah, 2022)

biorefinery, which combines three processes, including anaerobic digestion and composting, to exploit biogenic waste and harvest a scale of merchantable fuel and products (Awasthi *et al.*, 2022).

This shift toward such policies and sustainable technologies is necessary to overcome the difference between consumption and production demands and maintain the perfect balance between the economy, environment, and society. One such approach that meets this requirement is the circular economy approach, which paves the road to the effective use of

resources. Implementing systems that integrate various waste management technologies to create self-sustaining closed-loop systems can be put into practice, where agricultural waste is continuously recycled back into a resource and repurposed (Cobo, Dominguez-Ramos, and Irabien, 2018).

Additionally, combining models like life cycle assessment (LCA) into waste management provides a holistic analytical framework and quantitative assessment of waste management systems, including the main flows, waste quantities, composition, technology, and potential environmental impacts, which can play a pivotal role in improving management systems (Christensen *et al.*, 2020).

Ensuring collaboration among government agencies, the private sector, and communities to implement effective waste management strategies and facilitating partnerships between agriculture and industrial sectors to use waste as raw materials for industrial processes are some of the other management practices that can be integrated to promote resource efficiency and sustainable waste management.

26.4 Case studies and best practices

26.4.1 Case studies of successful implementation of sustainable waste management practices

Several studies have shown the successful transformation of agricultural waste into value-added products using a variety of strategies, such as using agricultural residues in the production of animal feed, paper, pulp, and compositing. They are also widely used matrices to create green fertilizer crop growth.

In Egypt, a case study of agricultural residues for the manufacture of paper, board, energy, and different fuels (solid, liquid, and gaseous) through pyrolysis, petrochemical replacements, and activated charcoal are all made from agricultural leftovers. A pulp and paper factory was created to produce writing paper, printing paper, rayon, dissolving pulps, and wheat straw, which is also used for animal feed. Nearly all varieties of pulp and paper may be made from these basic materials, according to research conducted by the cellulose and paper department (N.R.C.) (Fahmy *et al.*, 2017).

In Southeast Spain, the total amount of agricultural biomass produced by greenhouses in Almería has resulted in serious problems with waste management. This waste was formerly applied to the soil or used as animal feed. Since then, in an effort to enhance integrated agricultural waste management, public authorities have sponsored large-scale waste-collecting projects and encouraged agreements, municipal laws, and plans for rural cleanliness. Most growers appealed for subsidies to undertake self-management practices producing green fertilizer (Honoré *et al.*, 2019).

Another study was conducted in Spain to promote the management of agricultural waste residue. Composting and the production of green fertilizer have also been shown to be crucial factors in a more sustainable and circular agricultural production model. The generated compost and fertilizer are utilized in growing the main crops of tomato and pepper (Duque-Acevedo *et al.*, 2020).

According to research by Chamorro *et al.* (2022), agricultural production produces a lot of organic waste, including agricultural waste and food industry waste. Agricultural and food industry wastes derived from Kiwi cultivation and processing are considered as useful for the innovative applications in the food, cosmetic, and pharmaceutical industry which also promote a circular and sustainable economy.

Another study demonstrated the agricultural waste utilization as growing matrices for crops. In Nagaland, India rice is the principal crop of the states and eventually the producer of rice paddy residues. These rice paddy straw residues were significant applications for mushroom growing, which gives small and marginal farmers a source of extra revenue. Using paddy straw in a 250-bed mushroom growth chamber with a 3×6 m thatched cover, farmers have boosted their net earnings by Rs. 27,540.00 (Borthakur and Borah, 2023).

26.5 Policies and regulatory framework

26.5.1 Current global policies to promote sustainable management of agricultural waste

Globally, certification programs for many products in diverse industries have been created with varying scopes and objectives. These programs include fair-trade and organic agriculture sectors. In order to ensure that agricultural production met sustainability requirements and was both environmental and sustainable, a variety of certification programs, such as IFOAM and FAIRTRADE, were implemented for the farming industry. In order to prevent leakage, sustainable biomass production and GHG emissions should be taken into account in the sustainability standards for bio-based goods, bioenergy, and biofuels (Hamelin *et al.*, 2019; Mak *et al.*, 2020). Several government-funded agricultural waste management initiatives are specific to a nation and its states. Still, there are a few general guidelines and potential paths that might be taken in the direction of recycling and using agricultural waste.

To support the monitoring efforts, specific policies under the agricultural waste management program that are tailored to the realities of rural regions must be developed. The state must establish that for AWM projects to run well, the public must be informed of the law. Furthermore, it is necessary to popularize essential 3 Rs (reduce, reuse, recycle) regulations and legal papers (Koul, Yakoob, and Shah, 2022).

To address agricultural waste management and uphold agricultural food supply networks in Indonesia's Bandung regency, an extensive study has been conducted. A conceptual approach has been presented to encourage waste utilization, raise awareness, and alter people's behavior is based on the ADKAR (Awareness, Desire, Knowledge, Action, Reinforcement) change management paradigm. The approach highlights the significance of bringing about awareness, encouraging desire, imparting information, putting changes into action, and supporting and keeping an eye on the transformation process (Handayati and Widyanata, 2024).

EU directive 2018/2001 of the European Parliament and of the Council promotes the use of energy from renewable resources and the utilization of agricultural biomass. According to the EU, organic farming helps to accomplish environmental goals. The EU has emphasized the necessity of a new legal framework that makes it easier to produce and market fertilizers made from secondary raw materials, such agricultural by products. "Preserve and protect the environment and promote the efficiency of resources" is one of the EU's Common Strategic Framework's (CSF) strategic themes (Duque-Acevedo *et al.*, 2020).

The Ministry of Agriculture & Farmers Welfare, India reported that farmers may save up to Rs 2,000 per acre on manure expenses and improve soil fertility by using crop residue management methods subsidized by the Government of India. In India, 70% of the agricultural waste generated are used as fuel for homes and in the industrial sector. It is possible to turn residual waste into energy, biofuels, and biocomponents. In order to help India fulfill its obligations to the Sustainable Development Goals of the UN, Govt. of India has taken a number of steps to treat agricultural wastes to generate energy, recycle materials, and extract valuable resources. (Borthakur and Borah, 2023).

In recent years, the United Nations' goals to reduce food waste and increase sustainability have been recognized by many countries, demonstrating a shared commitment to tackling important environmental and social concerns. Reducing food waste throughout supply is highlighted in UN Sustainable Development Goal 12, which has led to the implementation of regulations by nations in pursuit of this objective (Shahmohamadloo *et al.*, 2022). For instance, the circular economy action plan of the European Union seeks to reduce food waste by 2030 by means of awareness camp standardized date labeling and assistance with surplus food donations. Similar to this, South Korea has implemented cutting-edge strategies, including volume-based pricing, required food waste sorting, and composting or biogas production from food waste. These programs support sustainability objectives and assist in lowering greenhouse gas emissions (Handayati and Widyanata, 2024).

26.5.2 Challenges in implementing policies and strategies for sustainable agricultural waste management

Governments may implement a number of policies for efficient agricultural waste management, including providing subsidies and promoting the involvement of both official and informal service providers and businesses with a connection to agriculture, rural population education, long-term agricultural waste recycling strategies, etc. However, due to a need for more awareness and an accurate understanding of these policies' implications on society and the environment, their macro-level implementation takes time and effort.

A study was conducted in rural China for biogas production in Household Biogas Digester (HBD) utilizing agricultural waste and livestock manure. Later, it was found that the HBD program would be successfully operational after eight years. However, the lack of technical training and subsidies for HBD operation were the major challenges to carrying on this strategy of agricultural waste management (Huang *et al.*, 2022).

Agricultural waste management techniques have some constraints, including the following: producing animal feed (possibility of toxicity), surface mulching (growth of weeds and pests), and pyrolysis (complex mechanism). To help address the limitation of fossil fuels and the effects of climate change, lignocellulosic biomass can also be used as a sustainable source of biofuel (biodiesel, bioethanol, biogas, and biohydrogen) and bioenergy production. Despite advantages, some of the challenges involved in these strategies are energy-intensive and require high investment costs (Koul, Yakoob, and Shah, 2022).

Several studies demonstrated that greenhouse gases might be produced throughout the composting process, which highlights the necessity for proper supervision procedures and raises serious environmental concerns (Ayilara *et al.*, 2020). Before being implemented, each strategy or policy should take into account the environmental impacts as well as appropriate procedural understanding.

26.5.3 Farmers' awareness and economic incentives

A transition to more sustainable techniques is required as the strain on agricultural production systems to attain global food security and stop environmental degradation growth. When it comes to agriculture, environmental sustainability includes sowing cover crops, rotating crops, and valuing variety, integrated pest control, precision farming, agroforestry techniques, and the combination of cattle and crops. The sustainable production would improve food security and lower poverty. Adoption of these sustainable methods typically necessitates financial incentives, a substantial amount of farmer labor, and national and local government and public-private partnership support (Piñeiro *et al.*, 2020).

Additionally, rural families need help (financial, technical, and troubleshooting) with composting and producing biogas (e.g., making compost boxes available to the public and selling them). Public knowledge and comprehension of waste management may be increased by effective communication and educational initiatives, which include the use of social media. In Ethiopia, for the implementation of land use policies, the authorities carefully consider the crucial role that farmers play in this program. They take care of farmers to be aware of and attentive to these policies in order to carry them out effectively (Ariti, van Vliet, and Verburg, 2018).

Another study was conducted in five European countries, which showed that incentives exist to adopt precision agricultural technologies within arable farming systems for sustainable agricultural production in the future (Barnes *et al.*, 2019).

The ADKAR utilization model in Indonesia is a method of bringing about promoting awareness, desire, knowledge, action, and reinforcement to educate the locals and farmers about the model's benefits and application in the context of waste management (Handayati and Widyanata, 2024).

26.6 Conclusion

Agricultural waste management is an essential component of sustainable agriculture, addressing both environmental and economic challenges. As the global population continues to grow, the increasing demand for agricultural products generates substantial waste, posing significant threats to human health, food security, and ecosystems. The improper handling of agricultural waste may lead to soil and water contamination and air pollution and contribute to climate change.

Effective management of agricultural waste involves adopting innovative technologies and sustainable practices. Techniques such as biochar production, anaerobic digestion, precision agriculture, composting, waste-to-energy technologies, and advanced biorefineries offer promising solutions. These methods not only minimize waste but also convert it into valuable resources like biofertilizers, sizers, and bioplastics. They also enhance the economic viability of agricultural practices, thus creating new job opportunities.

Integrated waste management (IWM) and circular economy emphasize reducing, reusing, and recycling waste, fostering sustainable resource use and environmental protection. Collaboration among government agencies, the private sector, and communities is vital for implementing effective waste management strategies. Moreover, the combined efforts may be directed toward improving the current rules, legislation, and policies pertaining to the prudent use or disposal of agricultural wastes; raising the money needed to build the fundamental infrastructure required for the utilization process; promoting valorization, industrialization of rural waste use, for a circular economy; and the purposeful encouragement of creative research and extension endeavors pertaining to technology use.

However, it still appears laborious and difficult for policy-makers to construct, operate, and maintain the waste management systems in agricultural communities and society that can bring back value-added goods, skill development, self-sufficiency, and economic progress. Ultimately, sustainable agricultural waste management must be encouraged to reduce environmental impacts, improve resource efficiency, and support the long-term viability of farming practices for the future generation's access to food and health, as well as reinforcement of the global economy.

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Chapter 27

Emerging trends and future prospects in agricultural waste management

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Chapter Outline

27.1. Introduction 477
27.2. Types and sources of agriculture waste 478
27.3. Environmental and economic impacts of unmanaged waste 480
27.4. Sustainable waste management strategies 483
27.5. Challenges in agriculture waste management 486
27.6. Innovative technologies and approaches 487
27.7. Future directions and research opportunities 487
27.8. Summary and conclusion 488
AI disclosure 488
References 489

27.1 Introduction

The population size of the world is increasing at an alarming rate, and the demand for food to feed this growing population has become a problem the world over (Crist, Mora, and Engelman, 2017). During the last five decades, agriculture production has risen by over fourfold due to a number of factors, such as expansion of agricultural land, the technologies provided by the Green Revolution, and the rising population (OECD, 2019). At the same time, it is estimated that 7 million tons of food is wasted every day (Soria-Lopez *et al.*, 2023). However, this tremendous rise in the production of food has emphasized the environment, thereby leading to severe consequences for vital resources, including the soil, air, and water resources. Rather than benefiting the social organism to which they belong, these changes negatively affect people's well-being and threaten the sustainability of life on Earth. The significant creation of food waste is one of the major issues in the agriculture industry. The Food Waste Index Report of 2019 revealed that global food waste production stood at 931 million tons, of which households' waste constituted 61%, food services 26%, and the retail sector 13%. Food waste is linked with more profound environmental issues, such as the necessity to develop an alternative means of energy in view of the regularly escalating deterioration of the environment and fuel prices. As a result, more attention has been directed toward the synthesis of bioenergy, including ethanol, biodiesel, and biogas from renewable raw materials (Pandit *et al.*, 2021). Greenhouse gas (GHG) emissions are also related to agriculture, which contributes 9-14% of the international emissions and is second to the energy industry, which emits 68% of emissions. Besides the contribution made to the emissions of GHGs, agriculture also produces large amounts of solid waste. The disposal and burning of agricultural residuals are improper in this sense, which poses significant risks to the well-being of people and the steadiness of the ecosystem. These

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methods not only increase levels of environmental pollution but also compromise food and energy sovereignty (Haghighizadeh *et al.*, 2024).

Crop residue burning is common in many Asian nations for several reasons, including shortage of labor, high cost, and limited access to technology. Moreover, due to the short duration of 15-20 days between harvesting and the next planting period, there are times when the farmers have no options other than to burn agricultural residues—this is because burning is the fastest way to clear an area. More regrettably, this impacts the loss of nutrients that would otherwise be found in the remaining food (Isa *et al.*, 2020). In view of these economic and energy as well as environmental implications of conventional agriculture, scientific studies have recently shifted toward the conversion of lignocellulosic-based agricultural residue for biofuel production and the production of industrial enzymes. Switching from nonrenewable energy sources to renewable energy is critically important for addressing every energy-related issue and reducing troubles in the environment. Specific forecasts suggest that the capability of renewable energy resources may indeed meet 20-40% of the entire worldwide energy requirement by 2050 (Nazir, Farooq, and Jamil, 2020). Grain residues, which make up most of the agricultural waste, are primarily composed of cellulose, hemicellulose, pectin, and lignin and, therefore, promise massive prospects for biofuel production. In this regard, the composition of agricultural waste has a range of cellulose 30-40%, hemicellulose 30-50%, and lignin 8-21% (Pandit *et al.*, 2021; Boix-Fayos and de Vente, 2023).

27.2 Types and sources of agriculture waste

Agricultural waste is undesirable or unsalable waste that results entirely from agricultural operations directly related to crop cultivation or animal husbandry with the primary goal of profit or livelihood. Some of the common types of agricultural waste generated from various agricultural operations are animal dung, post-harvest agricultural waste, agro-industrial processes, horticulture, crop cultivation, and solid waste from agricultural industries (Figure 27.1). If the waste is not

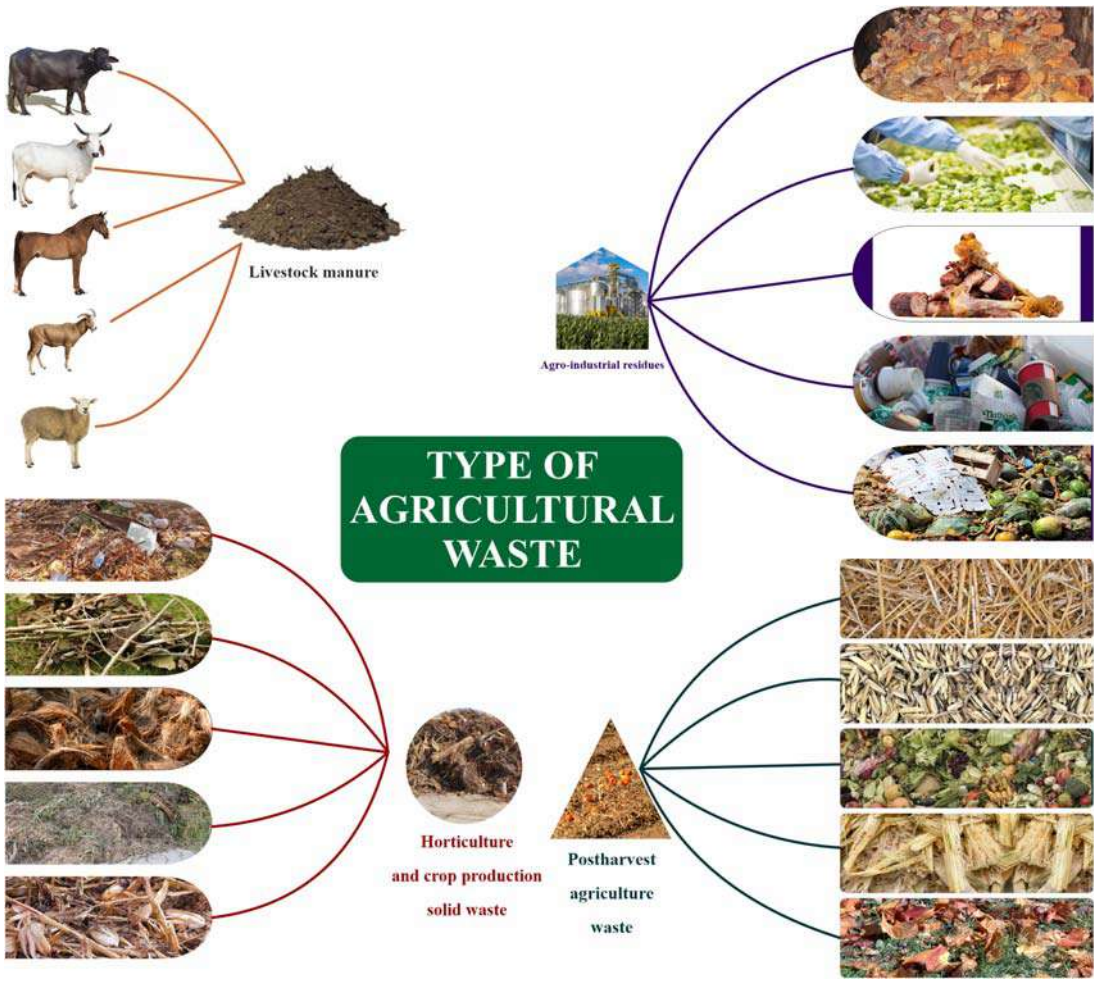


FIGURE 27.1 **Different kinds of major agricultural waste and their sources.**

managed correctly, it can lead to a variety of potentially adverse consequences depending on their inherent characteristics and properties (Mishra and Jolly, 2024). Agricultural waste generated from agro-industry and industrial agricultural waste potentially enhances resource recovery. Moreover, proper management of animal dung and post-harvest waste enhances soil fertility and is a source of biodegradation. Improper disposal of waste, such as burning, substantially increases soil erosion, greenhouse gas emissions, and air and water pollution (Singh *et al.*, 2023).

27.2.1 Livestock manure

Animal manure is a biological nourishment resource for plants' essential nutrients, including nitrogen (N), phosphorus (P), and potassium (K). Agricultural land is mainly used for cattle, pigs, and poultry, covering around 15.3, 0.10, and 1.3 million hectares, respectively, and animal sectors create around 120 million tons of manure each year. Animal manure is a source of organic material that benefits plants by providing inputs for changes in the soil's morphological and organic characteristics, as well as being helpful in the effective management of the soil (Loyon, 2018). However, the case is that if the manure is not properly handled, then there is a very high risk of environmental pollution because of animal operations (Khoshnevisan *et al.*, 2021). This involves the emission of nutrients, organic compounds, ammonia, and GHGs. The emissions in question include methane, nitrous oxide, and ammonium that result from the decomposition of carbon and nitrogen foodstuffs of animals. Excess in the elimination of manure in large quantities is undesirable since it creates severe issues in manure management (Ferraz *et al.*, 2024). This can lead to nutrient leaching, water pollution, eutrophication of water bodies, and the formation of toxic algal blooms, as well as a decrease in dissolved oxygen within water bodies. The above-discussed problems have detrimental effects on the water fauna. Furthermore, the use of manure is also associated with some disadvantages, namely, deterioration in the quality of the air on the Earth (Simon and Joshi, 2021). This is because the emissions from storage systems emit different gases, including methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2), hydrogen sulfide (H_2S), ammonia (NH_3), and volatile organic compounds (VOCs), among others (Amon *et al.*, 2006; Sommer and Hutchings, 2001). Composting is one good management practice as it recycles waste and turns it into fertilizer, while anaerobic digestion produces biogas (Kadam *et al.*, 2024).

27.2.2 Post-harvest agriculture waste

Plant straws, stalks, and husks, which are components of plants that remain after harvesting crops, constitute post-harvest agricultural waste. The combustion of post-harvest waste products, widely used in many places, produces particulate materials into the atmosphere that comprise carbon dioxide and different additional contaminants, therefore deteriorating both climate and air quality. These wastes fall under the heading of essential agricultural residue. Crop residue consists primarily of straw, husk, and stalks from harvested crops. The remainder can be utilized as fodder or degraded using various waste decomposers or combustion. These leftovers contain abundant cellulosic fibers (Clancy-Hepturn, 1998). Plant-based waste is a significant source of biological matter and necessary elements for plants. It is essential to employ such wastes as growth media with acceptable admixtures. It is challenging to sustainably dispose of these leftovers in greenhouses (Yörük *et al.*, 2024). Tomatoes are the most extensively planted crop, with an annual yield of 190 million tons globally a year (FAO. 2021, 2023).

27.2.3 Agro-industrial residues

Agriculture and livestock production are not solely for human consumption. They are employed for various purposes, and it is not unlikely that such operations generate agricultural solid waste. Wood processing and cuttings are easily identifiable as sources of agricultural solid waste. Paper production, which uses agrarian goods as raw ingredients, produces some agricultural solid waste. Bioactive chemicals are abundant in agrarian leftovers. These residues can serve as a backup supply for a variety of products, *viz.* biogas, biofuel, and mushrooms, as raw materials for studies and industries across the board. Utilizing agricultural and industrial wastes as raw materials can lower production costs and lessen environmental impact. Solid-state fermentation (SSF) is used to produce biofuels, enzymes, vitamins, antioxidants, animal feed, antibiotics, and other compounds from agro-industrial wastes (Sadh, Duhan, and Duhan, 2018).

Bio-waste products, which are leftovers from agro-industrial processing, are available in large amounts that can be utilized for the development of bio-based products (Wagh et al., 2024). These residues include, for instance, husks, molasses, bagasse, peels, hulls, and all sorts of remains that can be derived from plants (Vilas-Franquesa *et al.*, 2024). They are often generated during crop preparation for food, fiber, and other agricultural products (Khoshnevisan *et al.*, 2021). Industrial residues also contain a large quantity of lignocellulosic biomass that is mainly composed of cellulose, hemicellulose, and lignin (Mujtaba *et al.*, 2023). These components are beneficial as raw materials to produce biofuels,

bioplastics, biofertilizers, and other bioproducts. Another agro-industrial residue is rice husk, which contains high silica and can be used in the production of bio-silica, which has applications in various industrial fields (Ekwenna *et al.*, 2023). While valorizing agro-industrial leftovers, the environmental benefits include the reduction of wastes and GHGs, a reduction of fossil fuel, and a curbing of the environmental impact of waste disposal (Gupta *et al.*, 2023). Improved techniques in enzymatic hydrolysis have helped in increasing the production of fermentable sugars from lignocellulosic feedstock and bioethanol and other biofuels (Singh *et al.*, 2021). One of the agricultural residues that can be used is bagasse, a residue from sugar production, which can either be used for bioenergy production or the production of eco-friendly packing material.

27.2.4 Horticulture and crop production solid waste

Plant production in the horticulture industry: Fruits, vegetables, flowers, and decorative plants generate large amounts of solid wastes, trims, leaves, stems, roots, and other plant parts. Composting is a very effective method in dealing with horticulture waste wherein such wastes can be converted into compost, which serves as a natural fertilizer that may improve the quality of the soil (Lobo and Dorta, 2019; Raviv *et al.*, 2023). Landscape maintenance practices, including pruning of fruit trees and shrubs, produce large quantities of woody biomass while mowing lawns and collecting falling leaves are common. The accumulation of organic wastes in landfills may lead to the generation of leachate that pollutes the soil and water resources. Crop solid wastes are the agricultural solid wastes resulting from crop production and crop handling in a farming process and are usually produced during crop harvesting, for example, leaves, roots, and other non-edible parts of plants, naturally degrading and giving organic matter to the soil. Crop production solid wastes are one of the vast fractions of agricultural residuals generated at various stages of crop growing, reaping, and processing. Crop production solid wastes are produced by several activities that occur in crop production systems, such as planting, growing, harvesting, and processing. Such wastes include agricultural residues, husks, stalks, leaves, and other plant products, which are usually discarded or utilized inappropriately (Plakantonaki *et al.*, 2023). These materials are mainly derived from lignocellulosic biomass, which consists of cellulose, hemicellulose, and lignin in composition. This composition renders crop production solid wastes desirable for many purposes, such as in bioenergy production, composting, and feedstock for bio-products. However, there is mismanagement, for instance, when burning creates soil degradation and air pollution; proper management and usage enhance the agricultural activities' sustainability, reducing environmental pollution and enhancing the circular economy (Anil Kumar *et al.*, 2024). The burning of crops is a common practice in many agricultural regions, which releases particulate matter (PM), carbon dioxide (CO_2), and other GHGs, causing a decline in air quality, climate change, nitrogen deficiency, and poor crop yields. Sustainable crop waste residues can be utilized and transformed into biofuels, biofertilizers, and bioplastics, among others, giving farmers another way of generating income and making agricultural systems more sustainable (Singh and Prasad, 2022).

27.3 Environmental and economic impacts of unmanaged waste

The necessity for greater resource exploration arises from the world's increasing population growth. In recent decades, agricultural operations have expanded to fulfill the demands of a population that is rising at a rapid rate. Humans get their food, feed, and shelter from agricultural activity. Agricultural operations also contribute to the world's waste production, environmental risks, and health risks. A minimum of one-third of the food produced worldwide is wasted every year (Khan *et al.*, 2024). The primary causes of agricultural waste generation are the cultivation and processing of fruits and vegetables (peels, seeds, sugarcane bagasse, and woody cuttings), dairy and poultry farming (urine, feces, waste milk, bedding materials, birth tissues, bones, and blood), and other agricultural activities. Agricultural wastes release odors, affect the air and water, and endanger the environment. Chemical compounds that have been extensively used, particularly in the production of pesticides and chemicals, pose a significant risk to both the living and non-living components of our environment. These compounds, sometimes utilized without fully considering the environmental repercussions, will always impact not just the intended species but also several other species, either directly or indirectly. Therefore, it is anticipated that out of the total annual use of 2.5 million tons of pesticides on crops, only a mere 0.1% of the manufactured chemicals really reach the intended pests. Approximately 9% of unidentified substances contaminate the environment, causing harmful effects on human health, beneficial creatures, and the ecosystem itself by directly contaminating the soil and water.

Developed nations unequivocally use pesticides and experience the consequences, whereas underdeveloped countries endure the full force of these effects. It is well acknowledged that developing countries consume 25% of the world's pesticides, although these regions account for 99% of recorded pesticide deaths. The alarming statistic may be ascribed to

widespread and inappropriate use of pesticides, exacerbated by inadequate regulations, deficient healthcare infrastructure, and a scarcity of educational resources in these regions. The origin of pesticide usage may be traced back to the discovery of dichlorodiphenyltrichloroethane (DDT) by Paul Herman Muller in 1939, for which he was awarded the Nobel Prize in 1948. Subsequently, the use of pesticides has significantly escalated, resulting in a substantial presence of toxic pollutants in the environment. The behavior and persistence of these substances and their transformation products in the environment are influenced by several parameters, including their water solubility, soil adsorption coefficients (K_{oc}), octanol/water partition coefficient (K_{ow}), and soil half-life (DT50). There are some negative impacts of agricultural waste on the environment:

27.3.1 Impact of pesticide residue on animals

The majority of pesticides are contained in bottles, which are then immediately thrown into ponds or fields after usage. Of all the chemicals, 8% are still packaged in containers. Often, such wrappers and containers are swallowed, and this leads to the death of animals many times. In many nations, numerous pesticides are used in the breeding and production processes of crops.

Nevertheless, residual accumulation, migration, and metabolism in foods from animal use or indirect contamination in animal feeding may pose health concerns to people via the food chain (Jia *et al.*, 2024). Another reason is that the application of agricultural pesticides has reduced the number of valuable microorganisms in the soil due to the frequent use of pesticides. It is a fact that through the use of pesticides, the yield has increased. However, it has a very bad effect on the soil and the microorganisms that play specific roles in the soil, such as nitrogen-fixing organisms. For example, some types of herbicides slow down the use of nitrogen from the air in the formation of nitrates, which are needed for plant growth. For example, triclopyr inhibits the conversion of ammonia to nitrite due to reducing the population of bacterial *Nitrosomonas*; glyphosate reduces the numbers and activity of *Rhizobium* nitrogen-fixing bacteria; and 2,4-D decreases nitrogen-fixing ability in general.

Pesticide use also results in water pollution, which is another concern that harms the environment and most people. The possible reasons for pesticide pollution of water may be drainage, transpiration, and deposits on the surface of the plants during spraying, together with spilling. Past studies have shown that pesticide residues pollute water systems all over the world. For example, a survey accomplished by the US Geological Survey (USGS) during the early to mid-1990s reported that more than 90% of water and fish samples drawn from crucial river basins of the United States contained residual quantities of pesticides. To the author's shock, an Ordinance Survey of Britain revealed that the amount of pesticides that were present in urban streams was much higher than that in rural streams. Pesticide effects in the medical context can be acute and give rise to intense sensations of pain. Pesticides have been shown to provoke many adverse effects, including skin reactions, congenital disabilities, cancers, changes in the human genome, mental disorders, hormonal imbalances, and, in extreme cases, death. Chemical exposure over time leads to side effects on the neurological system; the effects of this are balance problems, memory loss, poor manual dexterity, immunological disorders characterized by irritation, allergies, and asthma. This is made worse by the farmers themselves who abandon the recommended ways of handling chemical pesticides. This lack of monitoring and oversight leads to the marketing of vegetables and other products bearing very harmful pesticide residues. The usage of pesticides in the production of vegetables may reach up to 90% of the total, while the share of cereal crop consumption is comparatively low. In addition, farmers initially ensure adequate protective methods to handle possible occurrences. Although pesticides are effective in fighting pests that affect productivity in agricultural facilities, people and the environment are, in various ways, endangered by these poisonous weapons used against different pests.

27.3.2 Effects of crop burning on the environment

Combustion of wastes such as straw and stubble after harvesting is referred to as crop burning and has substantial environmental repercussions. This approach is widely used to clear fields quickly and affordably, but it produces severe air pollution, soil erosion, and global warming. The impacts of agricultural burning on the ecosystem are clear and scientifically verified (Ravindra, Singh, and Mor, 2019). Air pollution is one of the worst repercussions of agricultural burning, as discussed before. During fire occurrences, considerable quantities of PM, CO, VOCs, NO, and Polycyclic Aromatic Hydrocarbons (PAHs) are emitted into the atmosphere from the burning of agricultural wastes (Venkatramanan *et al.*, 2021). These pollutants produce the creation of ground-level ozone and smog, which are considerable health concerns for individuals, including respiratory and cardiovascular ailments (Bargah, 2024). In a study conducted in the Punjab region of the nation that practices crop combustion, it turned out that during the span of the burning period, the quantity of PM2.5a, a particularly hazardous type of particulate matter, was higher, which contributed to an increase in the hospitalization of respiratory diseases (Gupta *et al.*, 2012).

Considering the consequences of environmental contamination, crop combustion dramatically affects the status of the soil. During burning, the tremendous heat immediately influences essential minerals and bacteria in the soil, drastically impairing the fertility of the Earth (Pradhan, Sinha, and Pandit, 2024). The loss of organic matter is also responsible for soil erosion and a deterioration in the water-holding ability of the soil. This leads to degeneration of the soil quality and renders it sluggish in terms of production beyond the fertility that it naturally supplies, thereby necessitating people to apply chemical fertilizers. Crop burning also impacts climate change owing to the significant emission of GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Filonchyk *et al.*, 2024). These gases allow heat to be trapped in the atmosphere, therefore increasing global warming and climate change. In accordance with the United Nations Framework Convention on Climate Change (IPCC), agricultural burning is seen as a substantial element of GHG emissions exacerbating the global climate challenge (IPCC, 2014). A case study of Haryana and Punjab in the northern area of India showed that smoke partly from rice straw alone released around 12 million metric tons yearly of carbon dioxide equivalent, thereby having a substantial influence in generating regional and global climate change (Sharma *et al.*, 2010).

In addition, agricultural burning produces ripple effects, therefore influencing adjacent places that might be far removed from the location of burning. The contaminants may travel extremely far, influencing the quality of air in nearby areas or nations. For example, crop-burning season in India leads to very bad air quality inside big cities such as New Delhi, which leads to an elevated incidence of air pollution-related mortality (Lan *et al.*, 2022). This is not an uncommon event in India; similar operations in other countries like Indonesia via the burning of peat hills have contributed to significant haze and air pollution concerns in the southeast region (Gaveau et al., 2014).

27.3.3 Crop residue effects on soil, water, and air pollution

It provides a haven for diverse viruses, fungi, and bacteria responsible for infectious illnesses. Inadequate management can result in air pollution, residential area damage, fires, and decreased soil productivity as they stifle microbiological activity (Majumder *et al.*, 2024). Residues are plant materials that remain in the field after agricultural commodities such as grains, seeds, or fruits have been collected, and they may be the most individual components of agricultural systems (Khan *et al.*, 2024). Fortunately, they were helpful in a variety of situations when used appropriately. However, their disposal, such as burning or dumping them to decompose on the ground's surface, was damaging to the atmosphere, water, and soil (Rathod, Saras, and Gondaliya, 2024).

Practically, if agricultural waste products were handled correctly, they helped to improve soil productivity while also lowering the potential of soil deterioration. They are damaging to the environment if not handled properly (Thadiyan, Kaur, and Gupta, 2024). There was the prospect of extracting advantages if these agricultural wastes were treated correctly since they influenced soil quality in terms of organic content, physical properties, and productivity (Kumar *et al.*, 2023). Burning was more detrimental because it reduced organic matter and beneficial bacteria in the soil when exposed to heat amplitudes. This approach rendered the land unproductive while also destroying natural processes that increased agricultural yield. Because rice straw has several applications, when burned, it directly depletes soil structure to organic carbon, resulting in a loss in agricultural production over time.

Furthermore, as soil biological matter declines, agricultural residues that protect the soil's surface from wind and water erosion shrink, increasing exposure to wind and water erosion, demonstrating that as organic matter in the soil decreases, susceptibility to water and wind erosion increases (Quinton and Fiener, 2024). Crop residues on the soil surface may act as a barrier, reducing runoff and increasing water penetration into the soil (Unger, 2023). Decomposing wastes may release nutrients such as phosphorus and nitrogen into water bodies via runoff, resulting in nutrient enrichment of lakes and rivers (Akinnawo, 2023). This causes excessive algae growth, which depletes oxygen in the water and kills aquatic life. The United States discovered that fertilizer runoff from agricultural waste in the Mississippi River Basin was a significant contribution to the Gulf of Mexico's "dead zone," an area of hypoxic waters incapable of supporting marine life (Rabalais, Turner, and Scavia, 2002). Burning agricultural waste is a common practice in many parts of the globe, particularly in countries with few resources, as a quick way to clear fields, but it also contributes significantly to air pollution. The combustion of agricultural waste produces significant amounts of pollutants, including PM, CO_2, CH_4, and nitrogen oxides (Chanana *et al.*, 2023). These pollutants cause smog and have serious health consequences for residents in nearby areas (Mahmood, Ali, and Jumaah, 2024).

Furthermore, the emission of greenhouse gases from garbage combustion contributes to climate change. Crop residue burning was responsible for a significant portion of the region's air pollution, particularly during the post-harvest season, causing a fast increase in respiratory diseases (Sharma *et al.*, 2010). The study also highlighted the transboundary nature of air pollution, with pollutants from crop burning in rural areas impacting air quality in major cities such as New Delhi (Ravindra *et al.*, 2023).

27.3.4 Pesticide and fertilizer residues: effects on aquatic environments

It is worth mentioning that contemporary agriculture hinges on the liberal utilization of fertilizers, pesticides, and other chemical supplements to boost yields and the pests' repellence (Gupta *et al.*, 2022). When pesticides are leached through irrigation, rainfall, or drainage to rivers, streams, or other water bodies, they directly affect them. The erosion of fertilizers, particularly those containing nitrogen and phosphorus, and their impact on the aquatic environment during intensified rainfall, irrigation, and drainage activities. Like the cases with POPs, pesticide residues, both herbicides and insecticides, can also be transported by water currents into various water bodies and even settle in the sediments. The loading of nutrients, especially nitrogen, phosphorus, and pesticides, into water bodies is defined as eutrophication, and this causes excessive growth of algae (in the case of fertilizer), known as algal blooms, which reduce oxygen levels in the water, thereby producing "dead zones" where aquatic life cannot exist. A large number of pesticides are lethal to non-target organisms such as fish, amphibians, and invertebrates. Some of the effects include reproductive failure, disruption of the food chain, modification in the behavior of species, change in species abundance and decrease in species diversity, and increased mortality rates (Kumar *et al.*, 2023). The consumption of drinking water sources that are contaminated with these chemicals leads to severe health problems such as cancers, endocrine disruptors, and neurological diseases (Singh *et al.*, 2023).

27.3.5 Effects of livestock manure on air, water, and soil

In the process of breakdown, livestock produces CH_4 and nitrous oxide (N_2O), which have a global warming potential 28-34 times greater than carbon dioxide over 100 years, according to IPCC (2021). Manure emissions of ammonia (NH_3) help in the formation of particulate matter in the air; people and animals with respiratory problems may experience complications. Another risk associated with animal manure is water pollution. This occurs when water is contaminated with manure. Then, it leeches into the groundwater or is carried by a stream of water bodies and contributes to water pollution through eutrophication (Smith, Crews, and Washington, 2023). Now and then, manure contains pathogens such as *Escherichia coli, Salmonella,* and *Cryptosporidium* that can become significant health threats if they contaminate drinking water sources. Althose livestock manure was preferred to enhance the fertility of the soils. Still, these, when used in excessive proportions, reached a point where they exceeded the capacity of the soils to absorb more nutrients, thereby pulling down fertility levels through nutrient imbalances that triggered the conversion of the soil into an acidic form (Khan *et al.*, 2022). There was an aspect of nutrient-induced toxicity that positively affected both crop yields and the microorganisms. Modifications in the population of microbes in the soil could impair essential processes in the soils, including nutrient cycling and the degradation of organic matter, leading to reduced fertility of soils and productivity of crops (Wang *et al.*, 2023).

27.4 Sustainable waste management strategies

On the other hand, ecological waste management aims to reduce the quantity of waste that is generated, to increase the quantity of waste that can be recycled, and to ensure that when waste has to be dumped, it harms the ecology around it to a minor extent (Ravindra *et al.*, 2023). It thus emerges that only by moving from the linear economy of disposal of products after use to the circular economy of management of waste for recovery and utilization can waste management be sustainable. The following are some of the sustainable approaches that can be used in the management of waste (Figure 27.2). The decision to generate as little waste as possible is one of the best steps one can take toward environment-friendly management of waste. This is reflected by embracing product design for durability and/or supporting behaviors and systems that entail reduced consumption (Balwan, Sharma, and Sharma, 2022). For instance, in waste management activities, which aim at reducing food waste, which is categorized under municipal solid waste, there has been an upsurge. In general, it is a situation that leads to the loss of approximately 40% of the foodstuffs, which calls for effective implementation strategies for achieving the desired reduction (Adeleke, Salihu, and Lawal, 2021).

Recycling in relation to the management of waste is, therefore, a primary and significant method. Modern advancements acknowledge the significance of reusing all the materials that are employed in people's daily lives, including plastics, metals, and electronics. Technologies have been improved regarding the recycling of e-waste since proposals have been put into practice to recover valuable metals with reduced contribution to pollution. More studies are still ongoing regarding the extraction of value-added products from agricultural and industrial wastes (Pinto *et al.*, 2023). Composting is also one of the methods employed in the disposal of organic wastes while producing fertilizers and conditioners for soils. Modern research indicates that people can apply vermicomposting, which means that certain earthworms participate in

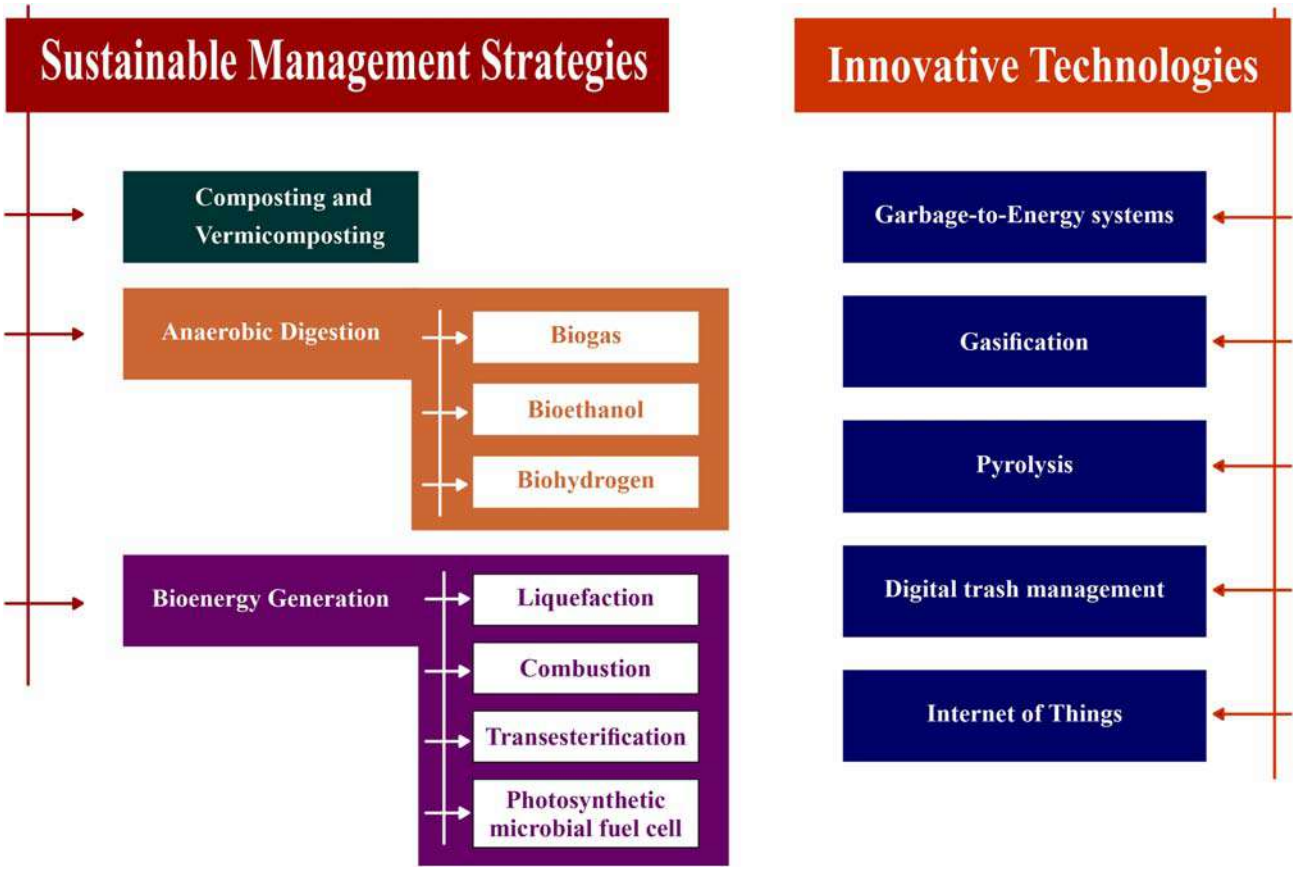


FIGURE 27.2 **Sustainable management and innovative technologies used in agricultural waste management.**

composting with a view to enhancing the compost quality. This method is also helpful in sustainable agriculture in preventing landfill waste and improving qualitative and quantitative assessment of the health of the soil.

Waste-to-energy technologies are the processes through which a person uses waste material that cannot be reused to serve valuable functions, such as the generation of energy such as electricity and heat. It cuts down the volume of waste that ends up in the dumping sites, but it also presents a type of renewable energy (Boloy *et al.*, 2021). In the recent past, the technological factor in Multi-Level Segregation (MLS) in garbage care has been improved by the use of advanced technologies with minimal harm to the environment. Evidently, waste management needs good policies and participation from people. Governments all over the world are slowly coming up with measures that require recycling and reduction of waste (Li *et al.*, 2023). Audience, publicity, sensitization, and awareness of different facets of sustainable living and engagement of the populace have been pivotal in the fight (Gulati, 2021). The application technology in garbage management had altered earlier approaches to that area that were suited to it. Sophisticated waste management with the assistance of sensors and the gathered data enhances garbage pickup and dumping. These solutions improve the performance of organizations as well as reduce costs; therefore, effective waste management is affordable for municipalities. There is a need to adopt an appropriate waste management regimen, and this calls for efficiency in the way resources are utilized. Societies can reduce and make improvements through the management of waste through theoretical and practical recycling, composting, and the use of new technologies where applicable (Zhang *et al.*, 2022).

27.4.1 Composting and vermicomposting

Composting involves the breakdown of organic matter through the agency of oxygen, and the product is an additive made from soil that appears black in color and is also known as compost (Goldan *et al.*, 2023). Vermicomposting involves using certain species of earthworms to improve the rate at which organic materials decompose to form vermicompost, which is usually richer in nutrients than regular compost. Both are essential for the regeneration of organic waste, diminishing the volume of waste sent to landfills, and enhancing the soil quality.

It is noteworthy that in the diagnosis of soil health, both processes are favorable and include the structure and fertility of the ground. Vermicompost further stands out by the number and motility of microorganisms contributing to the biological nutrient cycling and pathogenic agents' control at the site. Composting and vermicomposting are beneficial activities in that they greatly reduce the amount of organic waste that is dumped in landfills, thereby reducing the greenhouse gases emitted due to the decomposition of waste in the absence of oxygen. Economic benefits may decrease costs related to waste management and offer cheap sources of fertilizer to farmers, thus improving the economic sustainability of agricultural systems. Environmental impacts resulting from the application of compost and vermicompost can further enhance water quality through the reduction of hazards associated with the runoff of fertilizers and pesticides into water sources. In addition, it also supports the closing of the nutrient loop in agricultural systems since the development of these organic amendments.

Composting and vermicomposting have challenges, and public awareness and acceptance are sometimes an issue due to the insufficient knowledge of the general populace on the methods as well as the benefits of composting and vermicomposting. Since compost and vermicompost are made up of various feedstocks and undergo several processing steps, there is a likelihood of variations in the nutritional content of the final products. Such practices as standardization and quality testing, therefore, play an essential role in ensuring the quality of products that are produced. Although home and community composting are possible as a practice, the case with large-scale farms requires a level of investment in facilities and equipment (Dirks, 2021). Composting and vermicomposting are the paramount parts of environmental sanitation as well as agriculture. Recent advancements have found their effectiveness in enhancing the status of the soil, reducing waste output, and providing income. To avoid barriers and increase the application of these practices further, the process of research and raising public awareness should be sustained.

27.4.2 Anaerobic digestion

Some of the metabolic reactions that take place in anaerobic digestion are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the past, every phase involved specific microbial flora that could only work under non-aerobic procedures. Several factors contribute to Anaerobic Digestion (AD) process efficiency, including temperature, pH, substrate type, and retention time (Pasalari *et al.*, 2021). Substitution and modification have again been the focus of most of the existing studies on AD methods, with the aim of enhancing biogas production and efficiency in the degradation of complex organic materials. Multi-stage anaerobic digestion systems, for example, have attracted attention for their effectiveness in separating the diversified digestion phases in order to adjust the conditions required for the generation of the maximum level of biogas (Kunatsa and Xia, 2022). A scientific analysis of biogas production shows that efficiency can be boosted by considerable proportions by the use of two-phase and tri-phase systems as opposed to one-phase systems. A new direction of heat treatment is in combination with another method, anaerobic digestion (Liu *et al.*, 2023). Hydrothermal Treatment (HT) methods can treat high-moisture biomass feeds with the aim of enhancing the biomass's biodegradation and, consequently, the production of biogas. This method is particularly effective when applied to agricultural waste and food waste that, at times, takes a long time to break down due to its structure (Gomes *et al.*, 2023). As a result, the biota of anaerobic digesters, i.e., the microorganisms contained in them, must be known to promote efficiency. It has been with recent advanced high-throughput sequencing practices that other microbial types that participate in different steps of the digestion process have been discovered. For example, particular methanogenic archaea are involved in the conversion of volatile fatty acids into methane, and other processes are regulated by some of the operation parameters like temperature or type of substrate (Krohn *et al.*, 2022).

In the same way, the molecular biological developments that came at the tip of this initiative have helped us to study the temporal aspect of microorganisms and to gain increased control over the digestion process. This knowledge also helps to deal with standard problems such as the process's changing stability and the rates of biogas production connected with feedstock variation. For this reason, more people must accept anaerobic digestion since it has many effects on the environment in that it leads to the minimization of waste volume and the regulation of the release of greenhouse gases, which is associated with the release of methane during the decomposition process. Furthermore, the digestate, which is also produced, can be utilized to prepare concentrated nutrient solutions for sustainable use in agriculture.

The present AD work is helpful in contributing to the consideration of those economic contributions originating from the recovery of energy and valorization of waste. Biogas is employed in the production of electricity, heat, or even car fuel, suggesting that it produces energy that is renewable and not in any way related to fossil energy. New research introduced the possibilities of the economic activities available for micro-scale AD systems, especially in the rural context, to provide energy for cooking and illumination (Figaj, 2024), but some areas can be developed or researched further. The biggest

problem is that the process of hydrolysis needs to be optimized, while this phase is the most time-consuming in the process of digestion.

Further studies regarding the enzymatic and chemical pretreatment of the substrates to enhance their digestibility have to be provided. In addition, the results also showed that combining AD with other treatments like composting as well as aerobic digestion would yield additional benefits primarily expected to enhance the overall utilization of waste. The integration of digital technologies in monitoring and controlling AD processes can also lead to monumental improvements in the efficiency of operations and the yield of biogas. Hence, due to these facts, anaerobic digestion is a promising way of waste management and Renewable Energy (RE) generation.

27.4.3 Bioenergy generation

Bioenergy refers to energy generated from biomass, which, in this case, is feeds, crops, and any other waste products. There is a crucial role in the process of moving from using fossil fuels to using renewable energy resources. The interest in bioenergy has been occasioned by the increased focus on renewable energy and how best they can be implemented in addressing issues to do with greenhouse gases as well as energy insecurity. Modern scientific publications describe bioenergy as a resource that can become one of the critical suppliers of the world's energy needs; according to the technological prospects of biomass, this potential is approximately 200-500EJ in 2050 (Antar *et al.*, 2021). Feedstock is paramount when it comes to the creation of bioenergy. Present studies are carried out on the use of residues and co-products in agro-industries, food waste, and energy crops. For instance, *Agave* and *Opuntia* species for biofuel production have been used, especially in areas where regular crops cannot be grown.

Likewise, other wastes like post-harvest food and agro-industrial wastes are known to be potential feedstocks for bioenergy recovery, and studies in life cycle analysis show that the effects are sustainable on the environment and societal effects. Looking at the conversion point of view, bioenergy does not contradict such processes as digestion, fermentation, and thermochemical processes. Organic waste is suitable for disposal through anaerobic digestion, where biogas that is used in generating energy or as car fuel can be generated (Kumar and Prabhansu, 2022). More recent research work on microbial fuel cells and enzyme hydrolysis has also indicated some possibilities in the production of bioethanol from the lignocellulosic biomass material. Gasification and the pyrolytic process are becoming favorites as they use biomass to produce biofuel and charcoal (Basheir, 2024). The provision of energy generally characterizes these processes, and it helps contain the effects of climate change through carbon storage. Other improvements related to bioprocessing, like nanoparticles for increasing biogas production, are also in the process of being developed to improve the current bioprocessing (Manikandan *et al.*, 2023). It is thus evident that the environment stands to gain a lot from bioenergy production. Using waste materials, bioenergy enhances the reduction of landfill facilities' use, hence reducing greenhouse gas emissions associated with the decomposition of wastes.

Furthermore, bioenergy systems have the potential for reduced emission of air, water, and land pollutants. However, there are specific issues linked to the sustainability of this bioenergy feedstock and its implication on feedstock sourcing and land use policies that lead to deforestation and loss of biodiversity. The generation of bioenergy offers several optional economic returns, such as employment chances for people in rural regions and reduced energy import costs. For example, in India, the National Bioenergy Programme has been developed to enhance bioenergy capacity and promote domestic market opportunities. The program emphasizes the concept of distributed power systems that can enhance the benefits of the locals and diminish the use of fossil resources. Therefore, bioenergy production is fully compatible with the use of renewable energy sources that simultaneously solve problems of energy intensity, environmental impacts, and economic growth. Further studies and funding in bioenergy technology, along with related policies, are needed for them to be effective. There is a need for more research on the ability to utilize the feedstocks fully, improve conversion and efficient utilization, and the sustainability of the bioenergy systems.

27.5 Challenges in agriculture waste management

The disposal of agricultural waste has turned out to be an essential area of interest as the world population keeps growing, and agriculture practices are coming under pressure to feed the growing population. Appropriate handling and disposal of agricultural waste are crucial to the conservation of natural resources apart from the considerations for the human health of the agrarian workforce. Agricultural waste has a list of materials that includes crop residues, animal feces, agro-industrial residuals, and chemical wastes from fertilizers and pesticides; each type of waste has a number of disposal approaches, and those approaches can be technical and costly (Khan *et al.*, 2022). Lack of information dissemination and education to farmers sometimes pollutes water resources/environment by disposing of trash. Agricultural waste management, therefore,

is ineffectual (Rashid and Malik, 2023). The significant challenge that small-scale farmers face is that they need help to source the money to fund the waste treatment system, such as composting or anaerobic digestion facilities (Mor and Ravindra, 2023).

Lack of structures requires rural regions' garbage collection and treatment facilities for waste disposal methods such as burning or open dumping that are devastating to the environment. Agricultural waste requires supporting policies and laws; when existing, enforcement is often inadequate because of a lack of funds and corruption (Khan *et al.*, 2022; Zhang *et al.*, 2022). Also, sometimes there needs to be more research and development of efficient, economical solutions as well as the development of waste management adaptation to the needs of farmers (Boloy *et al.*, 2021; Liu *et al.*, 2023). Climate change makes the issue of disposing of agricultural waste worse in the following ways since climate change alters the circumstances in which waste management strategies are carried out (Li *et al.*, 2023). Agriculture is done in small parcels of land and thus cannot support the construction of large waste processing plants, and transportation of garbage can be costly and take time (Dirks, 2021). Furthermore, differences in the laws of the nations might lead to issues in the disposal of waste from imported agricultural products (Pasalari *et al.*, 2021).

27.6 Innovative technologies and approaches

The growing worldwide trash challenge requires new ways to manage waste efficiently. Traditional waste disposal technologies, such as landfilling and incineration, are unsustainable and hazardous for the environment, which is both a lose-lose (Durak, 2023). Garbage-to-energy systems on complex biological cycles turn non-recyclable waste into useful energy forms such as electricity, heat, and fuels and significantly reduce the amount of waste disposed in landfills (Zhang *et al.*, 2022). Pyrolysis and gasification are the advanced WtE technologies in this field. Gasification is the way it converts waste to syngas (a mixture of hydrogen, carbon monoxide, and methane), used for electricity generation as well as chemical manufacture (Wang *et al.*, 2023), while pyrolysis decomposes organic matter into bio-oil, syngas, and char, all of which can be further processed as fuel and other products (Lachos-Perez *et al.*, 2023; Yang *et al.*, 2024).

For more efficient solid waste management, we need new approaches to this evident international trash crisis, which is now overwhelming traditional methods of dealing with rubbish. The harmful consequences of these traditional "technologies" for garbage disposal can be surmised from the pollution problems in the cities and countryside as China faces a significant dilemma that must be solved. Today's garbage-to-energy systems convert nonrenewable waste products into gas and liquid fuels. This technology reduces air pollution, saves space in landfills, and reduces the need for incineration facilities (Zhang *et al.*, 2022). Most modern *gasification* and *pyrolysis technology* for WtE is advanced. During gasification, those organics are made into synthesis gas, which in turn is fed into turbines to make electricity or into factories for chemical reactions like ammonia or darkening (Wang *et al.*, 2023). In contrast, under pyrolysis, raw material such as coal can break down its constituent waste products into bio-oil, synthesis gas, and charcoal (which may be cycled back through a reactor) (Lachos-Perez *et al.*, 2023; Yang *et al.*, 2024).

Digital trash management utilizes technologies like the *Internet of Things* (IoT), big data algorithms, and blockchain to optimize collection and classification systems. These systems reduce the frequency with which garbage must be collected, cut down on operating costs, and lessen carbon emissions related to transporting waste. Because of blockchain technology, traceability and transparency in waste management have been born: all transactions from production to ultimate disposal create a secure witness record that cannot be altered. This effectively prevents illegal dumping and ensures responsibility throughout every link in this chain. In addition, these systems enable people, waste management providers, and regulatory authorities to communicate more fully. This results in waste management operations that are simpler and more efficient.

27.7 Future directions and research opportunities

The further evolution of agricultural waste management depends on the creation of new technological advancements and methodologies involving the effective harness of waste matters. Since the human population is increasing every day, the demand for food production that should be able to feed everybody increases as well. Therefore, proper management of waste becomes crucial. More effort should be directed toward improving the existing technologies for the conversion of waste into resources and exploring new ways of converting agricultural waste into biofuels, bioplastics, and other valuable products. For instance, trends in anaerobic digestion could increase biogas yields and reduce bio-waste management's ecological footprint. Considering the potential application of the available real-time data for the improvement of waste management methods by means of developed precision agricultural technologies, the rates of waste output and resource utilization may decrease. It is not sustainable agricultural technology, but another direction of research is the search for

microbiological and enzymatic processes for the transformation of lignocellulosic biomass into biofuels and biochemicals. The opportunity to produce active substances for biological products from C/P agri-residues remains an option for substituting fossil fuels, at the same time, enhancing the value of agricultural wastes (Singh *et al.*, 2023). In the future, there is a need to develop methods for the processing of agricultural byproducts for industrial use, as well as developing efficient methods to separate and purify the bio-products that emanate from the processing. Advanced techniques like pyrolysis and gasification open several exciting avenues of using agricultural residues for producing biochar, bio-oil, and syngas, which in turn can be used as a soil conditioner, fuel, or feedstock for industries. The optimization of pyrolysis and gasification also involves the invention of catalysts and reaction conditions that give high yields while having minor environmental consequences.

According to the principles of a circular economy, which presuppose the minimization, reuse, and recycling of resources, the strategy for the treatment of agricultural waste focuses on converting waste materials into valuable resources, thereby reducing environmental impact and promoting sustainable agricultural practices. The creation of combined composting and vermicomposting systems with crop production may produce a constant cycle of reusing nutrients. Examining agricultural waste as the feedstock to the biorefineries could envision new ways of developing biochemicals and bio-based materials that could be advantageous to the circular economy (Blasi *et al.*, 2023). Finally, creating a cohesive administration and management of waste that will be both economic and environmental will require a combination of agricultural science, environmental engineering, and economics. This includes assessing the impact of waste management strategies for socioeconomic implications and putting in place measures that spur farmers and agri-businesses into practicing sustainable waste management. The pattern to future studies should also focus on the barriers to the implementation of sustainable waste management practices, including the legal challenges, absence of structure, and cost restraints, and action plans on these problems should be suggested.

Sustainable landfill management is created with enhanced liner systems and leachate collecting systems to prevent soil and groundwater pollution to ensure the deleterious effects of heavy metals and chemicals. LFG (land filling gas) recovery equipment takes methane formed during the process of trash degradation, which may be used for the generation of electricity and thus reduce emissions of greenhouse gases. Compared to ordinary sanitary landfills, bioreactor landfills also have a shorter landfill operation life, which allows for faster site capping and possible land redevelopment. It reduces the current environmental problem through odorous emissions in most landfills and, at the same time, propels resource recovery and the circular economy goals. In the context of the implementation of EPR (extended producer responsibility), several sectors, such as electronics, packaging, and the automotive sector, adopted EPR, resulting in improvement in recycling rates and reduced waste. Product stewardship expands on the EPR for the involvement of the makers, retailers, consumers, and waste management involved in the product life cycle. Manufacturers have also begun to use biodegradable or easily reclaimable material to meet the set EPR, lowering the impact of their products on the environment.

27.8 Summary and conclusion

Management of agricultural waste is, therefore, crucial, as it impacts the economy and the environment in significant ways, thus calling for sustainable agriculture. It could cause deficit and degradation of the soil, pollute water bodies, and emit gases that are risky for human life in cases of uncontrolled waste from agriculture. However, with proper waste management strategies like composting, anaerobic digestion, and bioenergy production, agricultural waste can be recycled into useful products. For future work, the authors suggest the need to focus on the technologies for the conversion of waste to resources and identify the microbial and enzymatic possibilities for biofuel production, exploring the methodology of pyrolysis and gasification. Applying circular economy models in the management of agricultural businesses may lead to the use of a closed-loop system that improves resource productivity and lowers negative externalities. For optimization of the use of agricultural waste and encouraging a sustainable and viable agricultural economy, it is paramount to overcome the factors limiting efficient waste management, which include policy- and market-related factors.

AI disclosure

During the preparation of this work, the author(s) used QuillBot. The authors declare that the AI program was used to rework some sentences and check grammatical errors. The authors therefore take full responsibility for the publication of this book abstract. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Chapter 28

Potential agricultural waste management practices to contribute to a sustainable and circular agricultural system

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Chapter Outline

28.1. Introduction **493**
28.2. The potential of agricultural wastes in the circular economy 494
28.3. Potential of microbial biotechnology in agro-waste management 501
28.4. Valorization of agro-waste for livestock welfare 506
28.5. Challenges and opportunities 507
28.6. Conclusion 507
References **507**

28.1 Introduction

Agricultural waste refers to plant wastes from agriculture. These waste streams come from agricultural land and horticulture practices. Agricultural waste includes all crop portions not used for human or animal consumption. Crop leftovers mainly comprise stems, branches (when pruned), and leaves (Mohite *et al.*, 2022). It is estimated that, on average, 80% of the plants of such crops consist of agricultural waste. Controlling and utilizing agricultural waste appropriately can significantly contribute to ecological sustainability through pollution reduction, soil health improvement, and biodiversity enhancement. Simultaneously, energy security is boosted by producing renewable energy, promoting local energy solutions, and fostering economic resilience. This integrated approach addresses environmental and energy challenges and supports sustainable development and economic growth. Agricultural waste encompasses materials such as bagasse, bran, husks, peels, leaves, seeds, stems, and stalks and has a broad spectrum of applications beyond mere disposal. These byproducts of agricultural processes are valuable resources that can significantly contribute to various sectors, like soil

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improvement, fertilization, animal feed, and more (Phiri *et al.*, 2024). Lignocellulose, a significant component of agricultural waste, consists primarily of cellulose, hemicellulose, and lignin. These complex carbohydrates form the structural framework of plant biomass, making them an essential resource for various industrial applications, including biofuel production and the synthesis of valuable materials (Mujtaba *et al.*, 2023). To feed the expected population of 10 billion people by 2050, agri-food production must increase significantly. This increase will also lead to a higher wastage of agri-food (van Dijk *et al.*, 2021). Food wastes include dairy waste, meat and fish waste, vegetable waste, pulp garbage, and fruit peels. However, these food wastes are enriched with nutrients, making them ideal substrates for microbial growth and the production of various enzymes (Andler and Goddard, 2018). Furthermore, these wastes can be used as cheap raw materials for manufacturing primary and secondary metabolites employing microorganisms with commercial value.

28.2 The potential of agricultural wastes in the circular economy

The annual agro-residue significantly contributes to environmental issues (Shinde *et al.*, 2022). Agro-residue is around 25% of the world's biomass burning (Andreae, 2019). India's stubble burning, primarily from rice, wheat, sugarcane, and maize, accounts for 90% of its delicate particulate matter, contributing significantly to air pollution in many cities. A circular economy promotes sustainability by extending the life cycle of products through sharing, leasing, reusing, repairing, refurbishing, and recycling, thereby eliminating waste and enhancing resource efficiency.

28.2.1 Utilization of agro-residues in sustainable agriculture

A potential solution to the issue of agro-residue waste involves promoting alternative uses such as bioenergy production, biochar for soil enrichment, and livestock feed. Converting agro-residue into sustainable value-added products can provide an additional income source for farmers worldwide (Bala *et al.*, 2023). Encouraging farmers to adopt conservation agriculture techniques like mulching and no-till farming can mitigate residue burning and improve soil health. Implementing policies that support residue recycling and incentivize sustainable practices is imperative. Various studies have explored alternative uses for agro-residue. For example, silica-rich rice husks have been utilized in lithium-ion battery anodes (Liu *et al.*, 2013). Additional research has demonstrated that tomato residue can yield bioactive compounds, antioxidants, carbohydrates, and carotenoids (Coelho *et al.*, 2023). Sugarcane bagasse is utilized in the production of hydrogen, ethanol, and bio-oil, as well as in paper industries (Barciela *et al.*, 2023). Similarly, wheat straw's versatility in packaging, pulping, heating fuels, bioplastics, uranium absorption, and as a medium for microbes highlights its value as an agro-residue. Additionally, the multifaceted uses of rice husk ash as an adsorbent and fertilizer component in construction underscore its potential contributions (Kordi *et al.*, 2024).

28.2.1.1 Organic fertilizer production

Recycling agricultural waste is crucial for organic fertilizer production. Farmers recognize the importance of using a balanced combination of mineral fertilizers and organic manures to achieve optimal crop yield and maintain soil fertility. Agricultural wastes contribute a high organic matter fraction, enhancing the soil's physical, chemical, and biological properties and increasing crop productivity (Le *et al.*, 2022). Despite a decline in the use of organic manures in some countries with a long tradition of their use, the situation is changing due to energy crises, limited supply, and increased cost of mineral fertilizers. Organic manures benefit all crops, and their impact depends on factors such as timing and method of application, soil type, agroclimatic conditions, and soil moisture during crop growth. The focus of crop residues is on the equivalent fertilizer cost of the nutrients they contain.

The breakdown of lignocellulose bonds in crop residues through physical, chemical, and biological processes is beneficial as it enhances the nutrient content of the soil. Biological decomposition, accelerated by bacterial and fungal spores under aerobic and anaerobic conditions, is the most efficient method. Furthermore, microbial decomposition increases nutrient content through nitrogen fixation, phosphorus solubilization, and cellulose decomposition of the final product (Raczka *et al.*, 2021). Using bio-fertilizers from natural resources is a commendable and sustainable approach to enhancing soil fertility for small-scale farmers. Bio-fertilizers, containing living organisms, effectively enrich the soil with essential nutrients and minerals crucial for supporting plant growth and development (Ammar *et al.*, 2023). Derived from agricultural residues such as straw and corn stalks, bio-fertilizers represent a recycled product resulting from decomposition by bio-decomposers. Residues from leafy vegetables, fruits, and cereal crops serve as valuable sources of crucial nutrients like nitrogen, phosphorus, and potassium, as well as secondary and micronutrients such as calcium, boron, magnesium, and manganese.

28.2.1.2 Biochar production

Carbon-rich biomass carbonization products, known as biochar, have garnered significant scientific and public interest in recent years. Carbonized biomass from sustainable sources and sequestered in soils to sustainably enhance their agricultural and environmental value is termed biochar. Biochar is a pyrolytic organic material produced under oxygen-deficient conditions at temperatures ranging from 300°C to 1,000°C (Seow *et al.*, 2022). Due to its high carbon content, biochar has emerged as a potential solution for restoring degraded land, enhancing agricultural efficiency, and fixing carbon in various frameworks. Its high adsorption ability has the potential to immobilize heavy metals, pesticides, and hormones, prevent nitrate leaching fecal bacteria into waterways, and reduce N_2O and methane emission from soil (Nguyen *et al.*, 2023). The use of charcoal in agriculture waned considerably in the 20th century due to its increased value as fuel and the development of modern chemical fertilizers and pest control products. There has been a remarkable interest worldwide in the agricultural utilization of charcoal because many organic wastes can be treated and converted into energy using charcoal. Since charcoal is involved in renewable energy generation, waste treatment, soil fertility improvement, and carbon sequestration, charcoal has been best renamed biochar (Singh Yadav *et al.*, 2023). Recent studies show that agricultural residues, sewage sludge, forestry, and animal manure are the best sources of biochar. Crop residues and animal manure left in the field play an essential role in carbon sequestration, soil and water conservation, microbial activity, and agricultural productivity, making them a good source of biochar. Thus, biochar avoids the extra application of synthetic fertilizer and acts as compost (Sarfaraz *et al.*, 2020).

28.2.1.3 Soil fertility

The reduction of organic matter in agricultural soils is a significant global concern. This decrease directly impacts soil fertility, agricultural productivity, and various soil properties, including aggregation, structure, mechanical strength, compaction, and water-holding capacity. Recycling the biodegradable organic fraction of solid waste in agriculture can improve soil quality and provide sustainable waste management, reducing environmental deterioration caused by improper disposal. Soil organic carbon content is crucial for maintaining the fertility and sustainability of cropping systems. Organic amendments significantly increase soil organic carbon content, while inorganic fertilizers have the opposite effect (Sanjay *et al.*, 2019). The application of agricultural compost positively impacts soil properties, improving soil porosity, water retention, soil aggregation, sorption capacity, organic matter content, and the bioavailability of macronutrients (Ho *et al.*, 2022). A study on the effects of long-term (over 13 years) compost application (organic wastes such as pelletized organic compost from plant, animal, and biosolids residues, sheep manure compost, etc.) reported a consistent improvement in soil quality, with significant increases in organic matter (35%), electrical conductivity, total nitrogen, phosphorus, and potassium contents (Calleja-Cervantes *et al.*, 2015). These enhancements in soil fertility and productivity were attributed to the augmented organic matter and nutrient content in the soil, leading to improved nutrient supply, water retention, and reduced soil erosion and nutrient leaching (Zheng *et al.*, 2024).

Moreover, vermicompost is a popular and effective method for enhancing soil properties and fertility through biological oxidation and stabilization of organic waste. Vermicomposts contribute to higher porosity, surface area, and water-holding capacity, leading to increased retention of plant-available nutrients (Atiyeh *et al.*, 2000). Another study evaluating the impact of vermicompost and compost prepared from buffalo manure revealed significant improvements in various soil properties, including pH, cation exchange capacity, soil carbon, total nitrogen, phosphorus, potassium, available phosphorus, and available potassium content. Furthermore, treatment with vermicompost resulted in increased soil moisture, reduced soil water tension, and substantial reductions in soil detachment, leaching, water runoff, and leaching of NH_4^+ and NO_3^-, thus playing a vital role in minimizing soil erosion (Doan *et al.*, 2014).

28.2.1.4 Energy (bioethanol and bio-coal) production

Bioethanol is an alternative fuel that potentially reduces the dependence on fossil fuels. This fuel can be made from biomass, such as sweet potatoes, corn, and sugarcane, and non-food biomass that contain lignocellulose, such as waste crops and cereals, rice straw, etc. (Melendez *et al.*, 2022). Bioethanol produced from lignocellulose is the second ethanol generation and has a high energy cost due to the complex processes involved. Algae and microalgae content, like carbohydrates, can also be hydrolyzed to become sugar and can be fermented to produce bioethanol. Biomass feedstock selection is influenced by availability, cost, climate, and bioethanol production requirements, with sustainability and environmental implications crucial to minimizing negative impacts. Bioethanol production involves critical stages like pretreatment, hydrolysis, fermentation, and recovery (Sanni *et al.*, 2022).

28.2.1.4.1 Bio-coal. Bio-coal is a solid fuel produced through torrefaction. The torrefaction involves heating biomass without oxygen, which drives off moisture and volatile organic compounds, resulting in a dry, energy-dense product with properties similar to traditional coal. Bio-coal production from the slow pyrolysis of biomass is still a technology with relevant challenges that need to be consolidated in the worldwide energy market. Bio-coal is used as charcoal and a carbon source, and it is produced exclusively from wood logs to have the specific indexes of mechanical strength, density, and average size for steel production. The production of bio-coal is started with feedstock selection. Bio-coal can be produced from various biomass feedstock, including sawdust, wood chips, wood residues, agricultural residues, straw, rice husks, corn stover, sugarcane, bagasse, bamboo, willow, and miscanthus. Among biofuel feedstock, starchy materials such as corn, cassava, wheat, and barley are present.

28.2.1.4.2 Biodiesel production. The second most crucial bioenergy after ethanol is biodiesel, made from fats and vegetable oils, such as soy, rapeseed, and sunflower. Biodiesel can be obtained from various edible oil crops such as coconut, palm, soybeans, sunflower, and inedible oil crops such as *Calophyllum inophyllum, Ceiba pentandra,* and *Jatropha curca*. Used edible oils and fats are also inexpensive and readily available alternative resources for biodiesel production (Singh *et al.*, 2024).

28.2.1.5 Feed production

Feedstock generally includes various components of natural origin, such as trees, plant remains, animal remains, etc. Bioenergy such as ethanol offers a farmer a substitute for petroleum-based fuels and a market opportunity for livestock. It is a process that involves growing, harvesting, and extracting raw materials (crop residues, plants, minerals, and other natural resources) depending on the industrial processes. Efficient and sustainable feedstock production is increasingly important for ensuring resource availability and reducing environmental impact (Singh *et al.*, 2023). Feedstock production can contribute to sustainable development when managed responsibly and aligned with fundamental sustainability principles. Many feedstocks, like biofuels, responsible for energy production are renewable resources. It contrasts with finite resources like fossil fuels, making them potentially sustainable if managed correctly. Specific feedstock helps mitigate climate change by substituting for fossil fuels and reducing greenhouse gas emissions from land use change, fertilizer use, and transportation (Umakanth *et al.*, 2022). Sustainable feedstock production can incorporate practices that conserve biodiversity, such as agroforestry systems or preserving natural habitats within agricultural landscapes. Feedstock is crucial for several reasons, including its global abundance, role as a significant energy source, affordability, cleanliness, environmental friendliness, and sustainability. They are increasingly important today, providing energy and reducing greenhouse gas emissions, thus serving as a viable alternative to traditional fuels. Utilizing feedstock to generate energy is a direct goal of sustainable development. The feedstock production pays attention to generating energy and products due to energy security and increasing petroleum and natural gas costs. Chemical manufacturing and identification industries should develop novel routes and processes for bioenergy and commodities, and feedstock substitutes should be valorized. Bioenergy comprises several products, such as bioethanol, biodiesel, biohydrogen, and biogas. The primary attractive feedstock includes vegetation involving fast growth and significant annual collection (Wang *et al.*, 2021).

28.2.1.6 Mushroom and other fungi production

Mushroom cultivation methods can convert waste into valuable products and energy. Incredibly nutritious mushrooms have the potential to solve the global hunger crisis. Using spent mushroom substrate (SMS) for electricity generation and manufacturing biofertilizers and composts allows for the sustainable management of such agricultural wastes while minimizing greenhouse gas emissions. SMS in energy production, such as the production of bioethanol, biohydrogen, bioelectricity, and biobutanol, is a promising unconventional alternative for mushroom producers to use SMS to produce valuable products while also eradicating the problem of malnutrition, thereby promoting sustainable growth and clean energy production (Leong *et al.*, 2022). Over the last few decades, the increase in agricultural waste has drawn researchers' attention to this type of possible low-cost substrate for mushroom growing. The current status of mycoremediation technology, which involves the use of seven mushroom species to remediate waste, has been evaluated, along with an assessment of the safety of cultivating mushrooms on garbage. Cultivating mushrooms using agricultural waste as substrates offers numerous environmental benefits and helps reduce pollution on plantations and farms. Corn cob is recognized as a suitable substrate for mushroom production (Yu *et al.*, 2022). Paddy straw is also commonly used as a mushroom substrate, mainly for *Pleurotus* spp. (oyster mushrooms) (Subedi *et al.*, 2023).

28.2.1.7 Substrate in industrial bioprocesses

In a circular economy for waste management, substrates used in industrial bioprocesses are often derived from waste materials. This approach helps close the loop on resource use by transforming waste into valuable products. In the following subsection, we will highlight a few critical substrates for industrial bioprocesses.

28.2.1.7.1 Edible oil waste: A valuable byproduct. The edible vegetable oil industry generates solid waste during oil extraction, resulting in byproducts known as waste cakes. These cakes are formed during pressing, but they can also be found in forms such as coarse flours and pellets (Arrutia *et al.*, 2020). Hydrolytic rancidity in waste cooking oil arises due to lipid oxidation, moisture presence, prolonged storage, exposure to air, and the inclusion of industrial effluents that are high in carbohydrates, fatty acids, and proteins (Esfarjani *et al.*, 2019). Due to their high protein content, these residues are frequently used in animal feed. Specifically, the cake produced from soybean oil extraction is notable for its high protein concentration. There is growing interest in exploring its potential applications within the food industry.

28.2.1.7.2 Slaughterhouse, poultry, and egg processing waste: Managing byproducts effectively. The poultry, egg, meat, and related food processing industries produce substantial quantities of waste; the poultry industry, in particular, makes a tremendous amount of chicken feather waste, which is rich in protein, comprising approximately 90% keratin, and holds the potential for various industrial applications (Mozhiarasi and Natarajan, 2022). Slaughterhouse waste consists of skin, hair, feathers, horns, trimming residues, and other substances rich in organic matter, animal fat, and protein. Improper management of this waste can lead to significant health and environmental issues. However, this waste also serves as a valuable raw material for producing various commercial products.

28.2.1.7.3 Husk and malt bagasse: Potential uses and management strategies. The food and beverage industry generates substantial husk and malt bagasse as byproducts, particularly in brewing and milling. Often considered waste, these materials have significant potential for various applications if appropriately managed. Wet milling enables the extraction of starch, sugar, and oil from corn and, to a lesser extent, from sorghum for human consumption (Jackson and Shandera, 1995). As a result, the processing of these cereals generates substantial quantities of husk byproducts. These husk leftovers are utilized in various sectors of the agri-food industry, contributing to the production of several valuable commodities like vegetable oils, chocolate production, flour, and many more (Singh *et al.*, 2021). Wet bagasse is often contaminated with microbes, which makes it unsuitable for direct use in the food industry. To mitigate this, various preservation techniques, such as freezing, drying, and preservatives, should be employed to reduce its moisture content by up to 90%. Despite these challenges, bagasse is rich in fiber, making it a viable ingredient for candy, pastry, and other food products. Moreover, bagasse can be utilized in the creation of biorefineries, where it can serve as a raw material for producing biofuels and other biochemicals. It is also an excellent component for animal feed due to its high fiber content (Ajala *et al.*, 2021).

28.2.1.8 Novel application of xylooligosaccharides

Xylooligosaccharides (XOS) play a vital role in the circular economy by transforming agricultural and industrial waste into valuable products. This adds economic value, promotes sustainability, and aligns with the principles of reducing, reusing, and recycling materials. By integrating XOS production into circular economy models, industries can enhance resource efficiency, reduce environmental impacts, and contribute to a more sustainable future (Poletto *et al.*, 2020).

28.2.1.8.1 Food application of xylooligosaccharides. XOS are becoming increasingly popular as functional food ingredients for various reasons. First, there is an increase in consumer demand for health-enhancing foods. Second, scientific evidence supports XOS's health improvement and disease prevention benefits. Furthermore, XOS has distinct physiological and technological advantages over other non-digestible oligosaccharides, making them especially useful for self-medication and overall well-being. This has increased demand for XOS as a beneficial food component (Gupta *et al.*, 2018). XOS is resistant to low pH and high heat, making it suitable for low-pH juices, carbonated beverages, acidic dishes, and low-calorie sweeteners like xylitol. It also improves flavor in beverage formulas, making it a versatile ingredient (Martins *et al.*, 2023). XOS can be used to replace sugar and fat while also improving taste and texture. They promote mineral absorption, diabetic-friendly diets, and immunological function. These uses have received GRAS (Generally Recognized as Safe) certification from the Food and Drug Administration (FDA) as well as approval from Foods for Specified Health Uses (FOSHU) and the EFSA (European Food Safety Authority of India). XOS can be used as a sugar substitute to retain moisture and boost fiber content in beverages, fruit jelly, dairy, and bakery items. XOS has been utilized

as a cryoprotective agent to preserve Chinese meatballs and sensory qualities at only 1% XOS concentration. In addition, as texture modifiers, XOS has shown to be efficient in making robust biopolymer gels with higher shear stress (Penksza *et al.*, 2020).

28.2.1.8.2 Medicine application of xylooligosaccharides. XOS encourage the growth of good bacteria, which can help treat diarrhea, constipation, and other stomach-related diseases (Yang *et al.*, 2015). They also absorb poisonous compounds and dangerous bacteria in the intestines, strengthening the immune system and increasing illness resistance. This includes reducing the risk of obesity and metabolic disorders and preventing malignancies and diseases of the endocrine and cardiovascular systems. Many studies have found that XOS can reduce the activity of acute lymphocytic leukemia cell lines due to their cytotoxic effects (Huang *et al.*, 2022). XOS, derived from Melia xylan, has been studied for its potential to combat premature aging in skin health trials, showing anti-proliferative properties (Chen *et al.*, 2021). XOS has been used as a supplement to conventional medications for newborns, pregnant women, and patients with special needs such as high cholesterol, diabetes, and hypertension (Huang *et al.*, 2022). XOS formulate microparticles and hydrogels for drug delivery and therapy, mainly targeting gastrointestinal disorders (Gupta *et al.*, 2018).

28.2.1.8.3 Role of xylooligosaccharides as an antioxidant. XOS exhibit antioxidant properties that benefit health and industrial applications. Factors like polymerization degree and production method influence their effectiveness. GH30 xylanase-produced XOS has higher antioxidant properties (Valls *et al.*, 2018). XOS produced from corn cobs has been demonstrated to exhibit prebiotic features, including antibacterial actions, short-chain fatty acid (SCFA) generation, gut flora modulation, and *Lactiplantibacillus plantarum* growth stimulation. Furthermore, mixing XOS with *L. plantarum* S2 revealed high antioxidant activity in vitro. As a result, corn cob XOS has the potential to be an essential element in functional foods and nutraceuticals (Yu *et al.*, 2015). XOS produced from agricultural waste has grown significantly when used as the sole carbon source. These XOS also demonstrated antioxidant activity that increases with concentration. Therefore, XOS from agricultural residues have strong prebiotic potential and antioxidant properties, making them useful for food-related applications (Corim Marim and Gabardo, 2021). BsXyn11A and BsXyn10B are active xylanases capable of producing XOS. These enzymes were expressed in *Escherichia coli* and then purified and biochemically characterized. UXOS (glucuronoxylooligosaccharides), created enzymatically, has more potent antioxidant activity than AXOS (arabino xylooligosaccharides). UXOS, produced by a GH11 xylanase, contained neutral and acidic XOS with MeGlcA branching. In contrast, AXOS, which the GH10 xylanase family forms, is entirely composed of neutral XOS. The MeGlcA (methyl glucuronic acid) branches in acidic UXOS appear to play an essential role in increasing XOS antioxidant capacity, and this activity seems to grow with polymerization (Bouiche *et al.*, 2020).

28.2.3 Methods of organic fertilizer production

Composting is an eco-friendly method that converts organic waste into nutrient-dense soil additives, reducing waste, improving soil health, and mitigating climate change on a large scale. Composting converts organic waste into a uniform, eco-friendly material through exothermic bio-oxidation using carbon and nitrogen sources (Sayara *et al.*, 2020). This process can be used for plant nutrients, crop fertilizers, and environmental management. Factors such as temperature, pH, moisture content, and the carbon-to-nitrogen (C:N) ratio influence the composting process and its end products (Amuah *et al.*, 2022). Compost improves soil structure, reduces erosion, adds nutrients, and acts as a binding agent, enhancing chemical properties and plant nutrient availability (Ho *et al.*, 2022). Composting diverts organic waste from landfills, reducing waste volume and mitigating harmful gas emissions by breaking down organic materials (Nordahl *et al.*, 2023). It is an eco-friendly solution for organic waste management, providing a natural weed suppressant, beneficial insects, and enhanced soil health by creating a thick mulch layer (Onwosi *et al.*, 2020).

28.2.3.1 Traditional composting

These are the types of composting processes that require less economy and maintenance. The critical traditional types of composting are mentioned below:

28.2.3.2 Windrow composting

Windrow composting involves arranging large waste piles in long rows for decomposition and aeration. The piles are periodically turned to maintain temperature and air circulation. This economical method requires no specialized tools for aeration and can be modified for specific locations and circumstances.

28.2.3.3 Aerated static pile composting

In this system, the waste substrate decomposes without any physical turning or movement over 30 to 35 days. Perforated pipes provide aeration to waste piles, affecting decomposition efficiency and maintaining optimal temperature. Variations in aeration intensity create vertical temperature differences.

28.2.3.4 Vermicomposting

Vermicomposting is an eco-friendly recycling process that converts organic waste into high-quality compost, reduces heavy metals and toxins in sewage sludge, and decreases pathogens in organic matter, using specific earthworm species to enhance waste conversion and produce a safer agricultural end product. The two most essential earthworm species are the red wiggler or manure worm (*Eisenia foetida*) and another manure worm, the red worm (*Lumbricus rubellus*) (Yatoo *et al.*, 2020). These earthworms are cultivated on agricultural farms to consume organic waste, including all biodegradable materials. The manure they produce, known as "vermicast," is rich in nitrates and contains essential minerals such as P, K, Ca, and Mg. These vermicastings are excellent fertilizers and soil conditioners, significantly improving soil health and fertility. Vermicompost is rich in humic substances, such as humic acids, fulvic acids, and humin, which enhance plant growth and suppress disease through chemical reactions (Oyege and Balaji Bhaskar, 2023). The activities of beneficial microorganisms such as bacteria (e.g., *Bacillus*), yeast (e.g., *Sporobolomyces* and *Cryptococcus*), and fungi (e.g., *Trichoderma*) play a significant role in this process. Additionally, chemical antagonists in vermicompost, such as phenols and amino acids, contribute to its effectiveness in promoting plant health and protecting against diseases (Abad and Shafiqi, 2024).

28.2.3.5 Aerobic composting

The aerobic composting system is conducted in the presence of air at specific temperatures and pH ranges, where microbial consortia decompose biodegradable waste into a nutrient-rich bio-fertilizer. Maintaining the optimal rate of aeration during the aerobic composting process is crucial, as it helps to control odors and ensures efficient decomposition. The presence of adequate oxygen supports the activity of aerobic microorganisms, which break down the organic matter more effectively, producing high-quality compost with minimal unpleasant smells. Oxygen diffuses from the air into the moisture and is used by aerobic microorganisms for respiration and other metabolic activities. As a result of aerobic decomposition, carbon dioxide (CO_2), water, and heat are released as byproducts. The heat generated during this process creates micro-environments within the compost heap, which helps eliminate harmful pathogens and bacteria that cannot adapt to these conditions (Amuah *et al.*, 2022).

28.2.3.6 In-vessel composting

This system involves decomposing the organic fraction of waste within a closed container or vessel (rotating drums and agitated bags) under controlled conditions. These systems use instinctive aeration and mechanical agitation to enhance decomposition and expedite rapid composting. Motorized agitation breaks down particles for better contact between microorganisms and C-sources. The higher temperatures achieved in these vessels can eliminate several pathogenic activities, while continuous aeration helps remove odors from the system. This controlled environment optimizes composting, resulting in efficient and effective organic waste management (Michel *et al.*, 2022).

28.2.3.7 Co-composting of different waste substrates

This technique involves mixing two different waste substrates to enhance the composting activity by providing a suitable particle structure and density, creating necessary airspaces that improve aerobic microbial activity. The increased aeration supports a higher biodegradation rate, leading to more efficient and effective composting. Co-composting food waste can be an effective solution for processing it. Food waste can be blended with other substrates such as chopped hay, rice husks, wood chips, wheat straw, rice bran, sawdust, pig manure, poultry litter, and other similar biodegradable materials to maintain favorable conditions, including the carbon/nitrogen (C/N) ratio, void spaces, moisture, and nitrogen content. The pH can be adjusted by adding sodium acetate.

28.2.3.8 Composting using arthropods

Many species of insects are effectively utilized for reprocessing and transforming vegetal-origin waste. Blends of different types of waste at various decomposition stages attract essential species of arthropods whose life cycles conclude in the compost, enhancing the decomposition process. These arthropod species support the development of complementary

species. For example, arthropods like millipedes and black soldier fly larvae have been successfully used to compost various types of organic waste. Millipedes transform the waste substrate into fecal pellets, which modify the physico-chemical characteristics by decreasing the carbon/nitrogen (C/N) ratios, thereby improving the composting process (Ataíde *et al.*, 2020).

28.2.3.2 Anaerobic digestion

The anaerobic digestion (AD) process is a complex, dynamic system involving microbiological, biochemical, and physicochemical processes. Among the various methods for treating biowaste, AD is recognized as the most environmentally sustainable option, as it effectively diverts biodegradable materials from landfills. The process produces bioenergy and valuable byproducts, such as soil biofertilizers (Uddin and Wright, 2023). Since the AD process marks dual benefits, this process became an essential strategy for sustainable waste management and resource recovery. Several research studies have demonstrated the AD process as a robust and efficient treatment system. This efficiency makes AD an effective method for managing and processing organic waste, significantly reducing waste volume and producing valuable byproducts (Subbarao *et al.*, 2023). AD helps to convert organic matter in the absence of oxygen by different groups of specific microorganisms into CH_4 and CO_2. Thus, the process reduces the content of organic matter present in the waste, making it less polluting when discarded into the environment and suitable for use as fertilizer. The process also helps produce biogas with a high heat of combustion (Subbarao *et al.*, 2023).

28.2.4 Agro-waste-based reinforcement material production

The rising demand for agricultural products increases waste production, presenting significant disposal challenges. Annually, agricultural industries generate substantial amounts of residues. Improper waste disposal, without adhering to appropriate procedures, can result in environmental pollution and pose risks to animal and human health. Agro-waste can be categorized into animal waste, crop waste, food waste, hazardous waste, and toxic waste. Much of agro-industrial waste is either inadequately treated or improperly utilized, often leading to disposal methods such as burning or dumping in undesignated areas (Bhattacharyya *et al.*, 2024). Annually, over one billion tons of solid waste are generated, highlighting the need for effective waste management strategies and the importance of agro-waste utilization in sustainability efforts (Sharma *et al.*, 2023).

28.2.4.1 Bio-composites

In response to pressing environmental concerns and a growing emphasis on sustainability, the past decade has seen significant strides in green technology, particularly within materials science, focusing on advancing bio-composites. Within this domain, considerable attention has been directed toward using waste agricultural residues as a viable alternative to traditional materials like wood and plastics. Bio-composites, derived from agricultural byproducts such as cereal crop stalks, rice husks, and coconut fibers, have emerged as research and development focal points (Phiri *et al.*, 2023). This interest stems from abundant agricultural fiber production in many developing nations, where a substantial portion of agricultural waste is used as fuel.

28.2.4.2 Bioplastic

Bioplastic is a plastic material with either a biobased origin, biodegradability, or both characteristics. The term "biobased" indicates that the constituents of the material are primarily derived from biomass sources. Biodegradation refers to a chemical process wherein a material converts into water, carbon dioxide, and compost due to the enzymatic action of naturally occurring microorganisms in typical environmental settings.

For a polymer to qualify as biodegradable bioplastic, it must satisfy the following criteria:

- **Chemical composition:** At least 50% of the final composition of the polymer must consist of organic matter.
- **Biodegradation:** The polymer should degrade by at least 90% of its weight or volume within six months under controlled composting conditions.
- **Ecotoxicity:** Residuals remaining after biodegradation for six months must not pose a potential threat to plant growth.
- **Disintegration:** Microscopic fragments of the polymer components should be undetectable (less than 2 mm) within two months under controlled composting conditions (Hao *et al.*, 2024; Kim *et al.*, 2023).

Bioplastics, encompassing both biodegradable and nonbiodegradable variants, can be categorized into four primary groups based on their origins: directly extracted from biomass, synthesized from biobased monomers, synthesized from

petrochemicals, and produced by microorganisms. This classification reflects a diverse range of materials with varying properties and applications, presenting ecological alternatives to traditional plastics. Due to their physicochemical properties, polysaccharides are abundant, versatile macromolecules suitable for bioplastic production, allowing for physical and chemical modifications for various biomaterial applications. Cellulose, a prevalent polysaccharide derived from renewable sources, is primarily synthesized by plants. It is commonly extracted from various agricultural commodities such as rice, cassava, corn, wheat, and potatoes. Plant-derived cellulose typically accompanies hemicellulose, lignin, pectin, and other substances (Cheng *et al.*, 2023).

In contrast, bacterial cellulose exhibits higher purity, enhanced water content, and tensile strength due to its longer polymer chains. Cellulose derivatives, notably methylcellulose (MC), hydroxypropyl methylcellulose (HPMC), and carboxymethyl cellulose (CMC), are extensively utilized. Among these derivatives, CMC is distinguished for its exceptional film-forming properties, achieved through thermal gelatinization in conjunction with water-soluble polymers (He *et al.*, 2021). While starch demonstrates thermoplastic properties, its suitability as a bioplastic raw material is contingent on its specific structural features and chemical composition. Thermoplastic starch is obtained by disrupting starch granules in the presence of plasticizers. Extrusion processing, conducted under controlled conditions of low moisture content, elevated temperature, and pressure, facilitates the melting of starch granules, forming a homogeneous, continuous phase component. This molten starch component can be blended with other constituents to produce films or products (Mohamed, 2023).

28.2.4.3 Bio-bricks

Bricks, crucial in construction, are produced through traditional methods like mixing, molding, drying, and firing. However, these methods contribute to greenhouse gas emissions and resource depletion, especially in coal-based kilns. To address these environmental challenges, investments in modern kiln technologies are imperative to optimize carbonization processes and minimize emissions. Transitioning toward more sustainable brick-making practices is thus essential (Jonnala *et al.*, 2024). One approach involves incorporating agricultural waste products, such as rice husk ash (RHA) and sugarcane bagasse ash (SBA), into clay brick formulations. Incorporating 5% RHA and SBA by weight of clay reduced compressive strength and rupture modulus as the ash content increased (Channa *et al.*, 2022). The study found that bio-bricks with increased porosity, resistance to weathering, and enhanced efflorescence resistance have lightweight properties, reduced structural loads, and improved environmental sustainability. This makes them suitable for green building designs, highlighting the importance of waste material concentration. The use of wine waste products in the production of agricultural food products marked a significant shift in raw material selection (Maraveas, 2020). A study revealed that bricks with a 60:40 fly ash to red mud ratio exhibit superior strength, improved porosity, and thermal insulation, meeting IS:2042 standards.

28.3 Potential of microbial biotechnology in agro-waste management

Microbial biotechnology plays a crucial role in agro-waste management by providing sustainable solutions to enhance the valorization of agricultural wastes. With their diverse metabolic capabilities, microorganisms can degrade complex organic matter (such as fruits and vegetable wastes), detoxify pollutants, and produce valuable bioproducts such as biofuels, compost, organic fertilizers, etc. Harnessing microbial biotechnology facilitates the development of biofertilizers, biopesticides, biodegradable materials, and bioenergy from agro-waste, thereby enhancing soil health, crop productivity, and renewable energy production (Sinduja *et al.*, 2023). Moreover, advancements in microbial biotechnology have facilitated the development of biosensors and innovative labeling technologies to monitor food quality and safety parameters in real time (Meliana *et al.*, 2024). Despite significant advancements, several challenges hinder these technologies' widespread adoption, including economic viability, technological readiness, regulatory frameworks, and societal acceptance. Addressing these challenges requires collaborative efforts among researchers, policy-makers, industry stakeholders, and the farming community to foster innovation, develop supportive policies, and promote sustainable agricultural practices globally.

28.3.1 Fiber extraction

Fiber extraction from agricultural residues involves separating cellulose-rich fibers from non-cellulosic components, including lignin, hemicellulose, and pectin. These fibers can be utilized in various industrial applications, contributing to resource efficiency and waste reduction. The methods employed for fiber extraction influence fiber quality, economic viability, and environmental sustainability (Riseh *et al.*, 2024).

Retting, which involves the carefully regulated breakdown of pectinaceous molecules that bind fibers together, is an essential step in the extraction of fiber. It is a process that employs moisture and bacteria on plants to dissolve or rot away a large portion of the gummy materials and cellular structures around bast-fiber bundles, making it easier to separate the fiber from the stem (Tavares *et al.*, 2020). Various retting methods with their distinct advantages and limitations are mentioned below:

- Water retting is a widely used method for degrading plant stems or materials, soaking them in water for 7 to 14 days. This process degrades pectin, yielding uniform quality fibers, but faces challenges like high water usage and operational costs.
- Dew retting, or field retting, is a traditional method of decomposing harvested plant materials in the field over 14 to 21 days, commonly used in regions with limited water resources, but often results in inconsistent fibers.
- Enzymatic retting is a controlled microbiological method that selectively degrades pectinaceous substances in natural fibers. Despite its environmental impact, it may produce fibers with reduced mechanical strength, making it less suitable for durable industries.
- Chemical retting, a modified version of water retting, uses acids, alkalis, and salts to treat vegetable materials, producing long, clean fibers suitable for high-value applications but requiring careful management and waste disposal.
- Mechanical retting, or green retting, is a cost-effective method for separating fibers from plant materials. It involves decortication using equipment like ball mills, hammer mills, or crushing rollers, producing short fibers suitable for textiles and paper products (Sanjay *et al.*, 2019).

28.3.2 Biofertilizer development using agro-waste as substrate

Biofertilizers, derived from natural sources, contain living microorganisms that, when applied to seeds, plant surfaces, or soil, promote plant growth by increasing the supply or availability of primary nutrients to the host plant. Table 28.1 briefly mentions various types of biofertilizers, their functions, advantages, and limitations.

Utilizing agro-waste as a substrate for biofertilizer production is an innovative and sustainable approach, contributing significantly to the circular economy by recycling agricultural residues into valuable inputs for crop production (Kumar *et al.*, 2022). Biofertilizers can be developed from agro-waste using a series of processes: collection, pretreatment, microorganism inoculation, fermentation, maturation, and quality testing (Figure 28.1 and Table 28.2). Some studies have shown that biofertilizers prepared from agro-waste can increase crop yield. For example, a study found that biofertilizers made from watermelon, papaya, and banana wastes improved the physical properties of plant samples (Bala *et al.*, 2023). Another study found that the solid-state fermentation (SSF) method is an effective and economical way to produce biofertilizers from agro-waste. In this method, fruits are cut into small pieces, smashed, and then placed in a polyethylene bottle and left undisturbed for 30 to 40 days. The resulting soluble product is then filtered and used as an inoculum precursor for the following SSF process (Mattedi *et al.*, 2023).

TABLE 28.1 Types of biofertilizers and their functions.

Type of biofertilizer	Function	Agro-waste substrate	Advantage	Limitation	Reference
Nitrogen-fixing Biofertilizers	Convert atmospheric nitrogen into ammonia for plant uptake	Crop residues, manure	Enhances nitrogen availability, improves soil fertility	Requires specific microbial strains, optimal growth conditions	(Mahmud *et al.*, 2021)
Phosphate-solubilizing Biofertilizers	Convert insoluble phosphates into soluble forms for plant uptake	Organic acids from agro-waste	Enhances phosphorus availability, improves plant growth	Inconsistent effectiveness across soil types requires specific PSB/PSF strains	(Rawat *et al.*, 2021)
Potassium-mobilizing Biofertilizers	Mobilize potassium from soil minerals	Nutrient-rich agro-waste	Enhances potassium availability, supports plant nutrition	Requires optimal substrate preparation, strain-specific effectiveness	(Kour *et al.*, 2020)
Organic Matter Decomposers	Decompose organic matter, releasing nutrients and improving soil structure	Carbon-rich agro-waste (e.g., straw, manure)	Improves soil health and enhances nutrient cycling.	Requires controlled fermentation conditions, potential for variable results	(Phiri *et al.*, 2024)

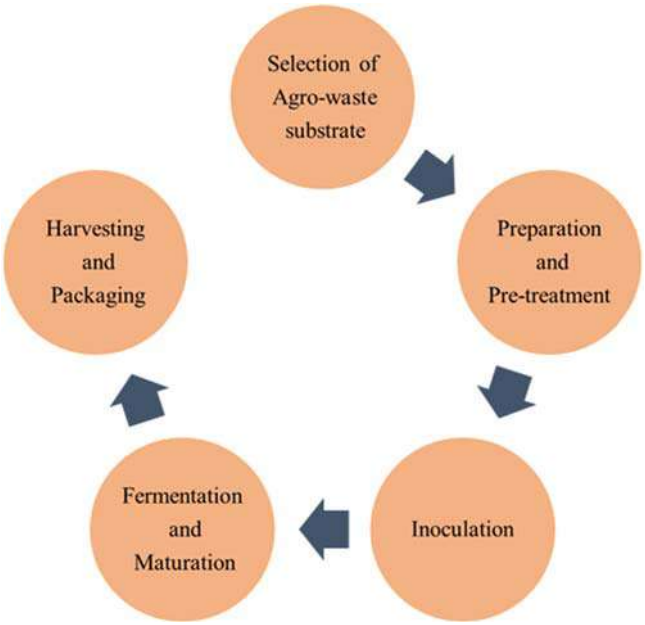


FIGURE 28.1 **Production of biofertilizers from agricultural wastes.**

TABLE 28.2 Various steps in biofertilizer production from agricultural wastes.

Step	Overview	Details
Selection of Agro-waste substrate	Choosing suitable raw materials for bio-fertilizer production	Typical substrates include crop residues (e.g., rice straw, wheat straw), animal manure, agro-industrial byproducts (e.g., molasses, bagasse)
Preparation and Pretreatment	Enhancing substrate suitability for microbial growth	Physical (e.g., grinding, sieving) or chemical pretreatments (e.g., composting, fermentation)
Inoculation	Introducing selected microorganisms into the prepared substrate	Maintaining optimal temperature, moisture, and aeration levels for microbial growth
Fermentation and Maturation	Microbial proliferation and metabolism of organic matter	Fermentation process duration varies (weeks to months) depending on substrate and microbial strains
Harvesting and Packaging	Collecting and preparing biofertilizer for distribution	Drying (if necessary) and packaging to ensure microbial viability and product stability

28.3.3 Microbe-mediated augmentation of agro-waste digestion

Microbe-mediated augmentation of agro-waste digestion leverages the metabolic capabilities of microorganisms to enhance the breakdown and conversion of agricultural residues into valuable byproducts. Microorganisms, including bacteria, fungi, and archaea, play a pivotal role in decomposing organic matter in agro-waste. They help degrade complex polymers such as cellulose, hemicellulose, and lignin into simpler compounds, catalyzed by their enzymatic activities, that can be further processed or utilized (Sanjay *et al.*, 2019). Cellulolytic bacteria, such as *Cellulomonas* and *Clostridium,* produce cellulase enzymes that hydrolyze cellulose into glucose units (Domingues, Timmers, and Granada, 2022). Hemicellulolytic bacteria such as *Bacillus* and *Bacteroides* spp. degrade hemicellulose into pentose and hexoses. White-root fungi (such as *Phanerochaete chrysosporium*) efficiently degrade lignin, making them crucial for lignocellulosic biomass breakdown. Some methanogenic archaea, such as *Methanobacterium* and *Methanosarcina,* produce methane from acetate, carbon dioxide, and hydrogen under anaerobic conditions and contribute to biogas production (Chukwuma *et al.*, 2021). Four key processes are enhanced by microbial augmentation (Figure 28.2).

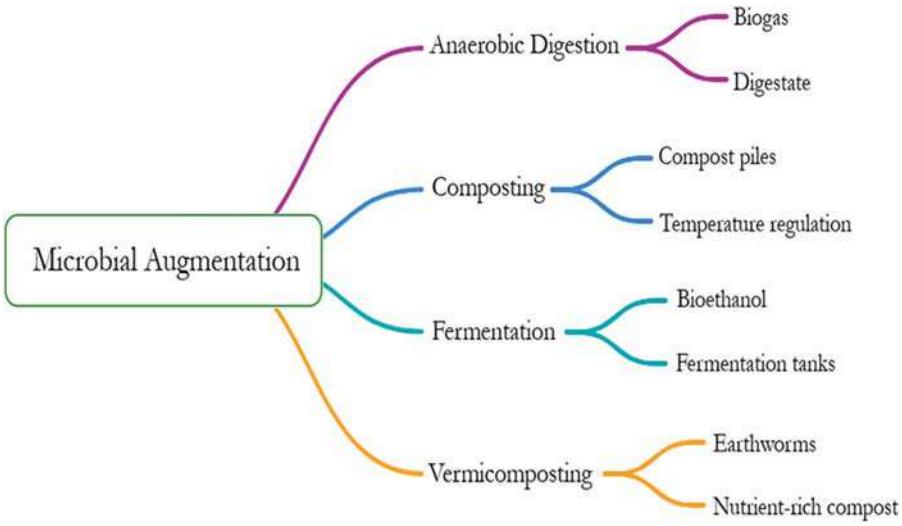


FIGURE 28.2 **Microbe-mediated augmentation of agro-waste digestion.**

28.3.3.1 Key processes enhanced by microbial augmentation

- **Anaerobic digestion:** It involves the breakdown of organic matter in the absence of oxygen, producing biogas (methane and carbon dioxide) and digestate (a nutrient-rich residue). Microbial consortia sequentially convert complex organic compounds into biogas, including hydrolytic, acidogenic, acetogenic, and methanogenic microorganisms. Enhancing the microbial community through inoculation with specialized strains can improve process efficiency, biogas yield, and the quality of digestate.
- **Composting:** An aerobic process in which microorganisms decompose organic waste into humus-like material. Introducing specific microbial inoculants, such as thermophilic bacteria and fungi, accelerates composting, enhances temperature regulation, and improves final compost quality.
- **Fermentation:** Fermentation processes, such as bioethanol production from agro-waste, rely on microbial action to convert sugars into ethanol. Yeasts (e.g., *Saccharomyces cerevisiae*) and bacteria (e.g., *Zymomonas mobilis*) are critical players in this process. Augmenting these systems with genetically engineered strains can increase ethanol yield and process robustness.
- **Vermicomposting:** Vermicomposting utilizes earthworms and microorganisms to convert organic waste into nutrient-rich vermicompost. Microbial augmentation, including introducing nitrogen-fixing and phosphate-solubilizing bacteria, can enhance the vermicompost's decomposition rate and nutrient profile.

28.3.4 Pathogen detection in agro-waste

Effective management of agricultural waste is crucial for sustainability, public health, and environmental safety. Pathogens in agro-waste can pose significant risks to human and animal health, contaminating soil, water, and crops. Therefore, accurate and timely detection of pathogens in agro-waste is essential to mitigate these risks and ensure safe reuse or disposal of waste materials. Pathogens such as *E. coli, Salmonella, Listeria,* and viruses in agro-waste can lead to foodborne illnesses if they contaminate crops or water sources used for irrigation. Detecting these pathogens early helps prevent disease outbreaks (Bell *et al.*, 2021). Animal manure, a common component of agro-waste, can harbor pathogens like *Cryptosporidium* and *Campylobacter,* which can infect livestock and wildlife (Pumipuntu and Piratae, 2018). Monitoring these pathogens is vital to protect animal health and productivity (Figure 28.3).

28.3.4.1 Methods of pathogen detection

- **Culture-based methods:** A particular method involves isolating and growing pathogens on selective media. While reliable, these methods are time-consuming and may not detect viable but non-culturable (VBNC) pathogens. However, it is labor-intensive and time-consuming.
- **Molecular methods:** PCR-based methods amplify specific DNA or RNA sequences to detect pathogens, including quantitative PCR (qPCR) and reverse transcription (RT-PCR). These methods are susceptible and can detect low levels of pathogens. Next-generation sequencing (NGS) provides comprehensive profiling of microbial communities,

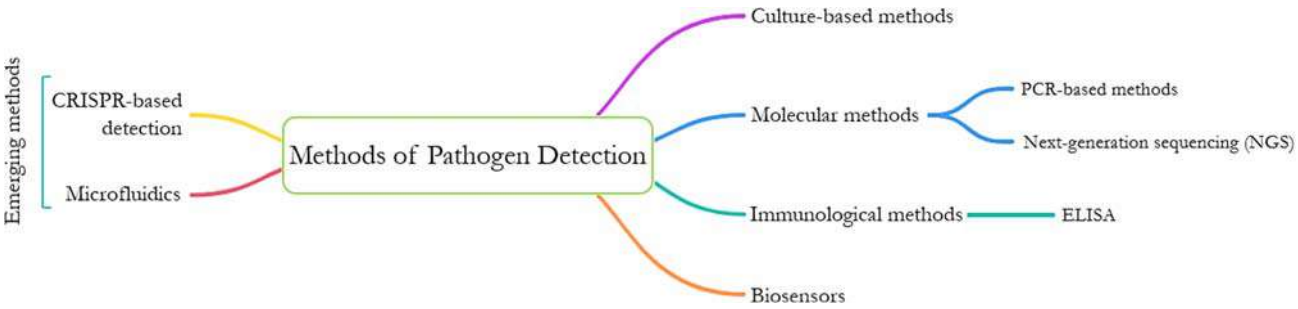


FIGURE 28.3 **Various methods of pathogen detection in agricultural waste.**

including pathogens. It can identify multiple pathogens simultaneously and detect novel or emerging pathogens. However, these are costly and require significant bioinformatics expertise.

- **Immunological methods:** Methods like ELISA can detect pathogens using antibodies specific to target antigens. It is commonly used for detecting bacterial toxins and viral antigens. These methods are cost-effective for large-scale screening.
- **Biosensors:** Biosensors utilize biological recognition elements, such as antibodies or nucleic acids, coupled with a signal transducer to detect pathogens. They offer rapid and on-site detection capabilities. However, sometimes, the development and calibration of sensors can be complex and require frequent maintenance.
- **CRISPR-based detection:** CRISPR-Cas systems, developed initially for gene editing, are being adapted for pathogen detection. CRISPR-based assays offer high specificity and can be combined with isothermal amplification techniques for rapid and sensitive detection. However, this method is still in the early stages of development.
- **Microfluidics:** Microfluidic devices integrate multiple laboratory functions on a single chip, enabling rapid and automated detection of pathogens from small sample volumes. These devices combine sample preparation, amplification, and detection in one platform (Aladhadh, 2023).

28.3.5 Biosensors and smart labeling to reduce food waste

Food waste is a significant global issue, with approximately one-third of all food produced for human consumption lost or wasted annually. Effective management and reducing food waste are essential for improving food security, conserving resources, and reducing environmental impacts (Sanjay *et al.*, 2019). Biosensors and smart-labeling technologies offer innovative solutions to monitor food quality and safety, reducing food waste across the supply chain. Smart-labeling technologies provide dynamic information about food products' conditions and history, including time-temperature indicators (TTIs), radio-frequency identification (RFID) tags, and QR codes. These technologies enhance supply chain transparency and enable better decision-making regarding food quality and shelf life (Bhatlawande *et al.*, 2024). Some smart labels are TTIs, RFID tags, QR codes, etc. These smart labels help in reducing food waste. Smart labels offer real-time food quality data, improve inventory management, enhance the supply chain, and aid consumer decision-making. They facilitate rapid traceability and targeted recalls, reducing food waste (Wang *et al.*, 2015).

28.3.6 Antibiotic resistance and multidrug resistance gene monitoring

The rise of antibiotic-resistant (AR) and multidrug-resistant bacteria (MDR) has been described as one of the most severe threats to global health. Agriculture, practiced explicitly on farms through antibiotics in animal husbandry, is a leading driver for developing and disseminating resistance determinants. There is a dire call for surveillance of resistance genes to antibiotics and MDR genes in agricultural waste to reduce the risk to public health (Zhang *et al.*, 2022). The impact of antibiotic-resistant bacteria on public health can be high since such pathogens may gain entry into food chains with contaminated agricultural products and cause serious health threats to consumers. It is much more difficult to treat infections by AR and MDR pathogens, increasing morbidity and mortality rates. In addition, the resistance genes in agro-wastes can out-scatter into the soil and aquatic systems and diffuse through environmental and human-associated microbial communities. This environmental reservoir aggravates the already acute global problem of antibiotic resistance (Nadgir and Biswas, 2023). Therefore, AR and MDR gene monitoring is necessary to ensure compliance with regulative standards and the conduction of strategies to reduce the spread of resistance to guarantee agro-product safety and quality.

Monitoring antibiotic resistance and MDR genes has a broad range of applications. Tracking AR and MDR genes in manure, compost, and other agricultural wastes in agriculture waste management reveals the impact of antibiotic use in

agriculture on resistance spread. It guides the implementation of waste treatment practices for resistance reduction (He *et al.*, 2020). This would be assessed based on the presence and levels of resistance genes in soil and aquatic systems affected by agricultural runoff, giving an idea of the environmental dissemination of resistance that informs mitigation strategies. Surveillance programs set up with AR and MDR gene monitoring provide early warnings of trends in emerging resistance, thus enabling public health interventions in time to initiate prevention and avoid pathogen spread.

28.4 Valorization of agro-waste for livestock welfare

Food disposal has increased due to rising population and nutritional expectations, leading to severe ecological and financial effects. It is feasible to recycle food scraps into healthy livestock nutrition, minimizing scrap disposal and offering the livestock an alternative source of protein. Incorporating food scraps for livestock nutrition provides an alternative for solving issues regarding waste control and food safety while reducing the requirement of regular feed production. It promotes a circular economy by establishing a closed-loop framework, resulting in reduced ecological degradation. Consequently, food scraps as livestock feed provide a long-term remedy for handling waste, ensuring dietary safety, preserving resources, eliminating environmental damage, and maintaining a circular economy (Nath *et al.*, 2023).

28.4.1 Agro-waste-based prebiotics for aquaculture

Bioactive molecules like phenolics, terpenes, and β-glucans have antioxidant, antibacterial, gut microbiota, and immunity-modulating properties, making them beneficial for fish farming and maintaining health. Cereal crop leftovers are used as antioxidants in fish diets, with maize silk extracts and sorghum phenolic substances enhancing antioxidant properties and slowing lipoprotein oxidation. Fruit processing debris, including banana and orange peels and mushroom stalk waste, are being explored as antioxidant sources to enhance hepatic antioxidant response and protect against oxidative stress (Leyva-López *et al.*, 2020). A study on *Labeo rohita* (rohu) fingerlings fed castor protein isolate (CPI)-based diets found higher growth stages, feed utilization ratios, and protein retention than the control group. CPI had better protein content, better amino acid profiles, and decreased antinutritional factors. It also increases gastrointestinal enzyme function without causing metabolic stress. The diet was found to be comparable to the control.

Additionally, biochar made from sugarcane bagasse and paddy straw was tested on genetically modified farm tilapia (Jayant *et al.*, 2021). The study examined the effects of biochar on the development and hematological variables of genetically modified farm tilapia. Biochar, made from sugarcane bagasse and paddy straw, was fed to fish for 45 days. The diet significantly improved growth parameters, weight gain, and feed conversion ratios. It also enhanced hematological indicators, reduced catalase activity, and increased amylase and lipase activity (Kara *et al.*, 2023).

28.4.2 Agro-waste-based prebiotics for livestock and poultry feed

Agro-waste products can generate quality feed for the poultry sector by replacing conventional feed and reducing expenditures to a great extent. Addition of rice bran oil (RBO) to broiler chicken diets increased body weight gain and feed conversion ratio. However, it did not affect feed consumption or erythrocytes. As RBO content increased, so did heterophils, lymphocytes, and monocytes. The diets with more RBO had higher total cholesterol content and increased IgG and IgM concentrations. The study suggests that supplementing rice bran concentrates in optimum doses can improve growth performance and lower cholesterol levels (Kang and Kim, 2016). If properly utilized, agro-residues can provide valuable biomass resources for livestock nutrition and global caloric and protein supply, with studies showing economic and efficient use after recycling. A survey of horses found that dried grape pomace (DGP) could improve their wellness by increasing their digestibility of specific nutrients. The study used blood serum biochemical indicators and total tract digestibility of dry matter, organic matter, crude protein, acid detergent fiber, and neutral detergent fiber. The results showed that the E2 (feed rations + 400 g of DGP) group had lower digestibility indices for all nutrients compared to the control (C) and E1 (feed rations + 200 g of DGP) groups. This suggests that DGP could improve horse health without negatively impacting their health (Kolláthová *et al.*, 2020).

28.4.3 Probiotic propagation using agro-waste

Recycling agro-waste to generate livestock feed provides a sustainable and green means to deal with malnutrition. Besides being costly, conventional feeds have been connected to harmful chemicals and antibiotic resistance. Thus, livestock feed incorporating advantageous microbes can lower intestinal infections, balance the pH of the rumen, increase productivity, and improve the overall well-being of the livestock. A study explored the benefits of incorporating *Lactobacillus fermentum* into poultry feed using food and agri-residue. It compared probiotic-fortified feed with regular starter mash and

ground corn and tested against *E. coli*. Results showed similar growth performance and decreased *E. coli* levels in chicks fed different diets, suggesting probiotic-fortified diets as an effective alternative (Sanjay *et al.*, 2019). Bioactive compounds in fish farming have led to the development of sustainable alternatives to antibiotics and other antibiotics in marine food industries using raw residuals. Current scientific trials focus on using biomolecules and enzymes as feed additives to enhance fish dietary value and immunity, with fermented methods gaining prominence for their efficient inhibiting activities (Thazeem *et al.*, 2022). A study investigated the microbial transformation of olive cake (OC), a byproduct of Morocco's olive oil industry, utilizing solid-state fermentation with chosen filamentous fungus to increase its dietary value for ruminant feed. Fungi *Beauveria bassiana, Fusarium flocciferum, Rhizodiscina cf. lignite,* and *Aspergillus niger* were grown on OC for 15 days, resulting in a 94% protein spike and a significant decrease in total phenolic, flavonoid, and condensed tannin content, thereby improving OC nutritional value and feed value (Chebaibi *et al.*, 2019).

28.5 Challenges and opportunities

The use of agro-residue presents an environmentally friendly and economically viable solution. The innovative approaches to agro-residue utilization, backed by extensive research and development, present efficient alternatives to conventional disposal methods and hold promise for leveraging today's available technology. The primary advantage of using agro-waste as a substrate is its cost-effectiveness, as agro-waste is readily available and inexpensive. Recycling agro-waste reduces environmental pollution and greenhouse gas emissions, aiding in waste management. It also enriches the soil with organic matter and beneficial microorganisms, improving soil structure and nutrient availability. However, there are several challenges associated with using agro-waste as a substrate. These include inconsistent quality and efficacy, the need for regulatory and market acceptance, and the requirement for novel microbial strains and production techniques to meet market demand. Agricultural waste is causing environmental issues, necessitating further research on recycling for organic fertilizers to promote sustainable agriculture. Additionally, literature on agro-residue utilization, both conventional and non-conventional, is limited, highlighting societal barriers and potential solutions for sustainable future use.

28.6 Conclusion

Agro-industrial wastes are rich in nutrients and bioactive compounds, making them suitable for downstream industrial processes. These residues can support microbial populations through fermentation and can be used as solid support in solid fuel production. This reduces production costs and promotes waste recycling and environmental sustainability. Crop residue management requires sustainability, stakeholder empowerment, and coordinated thinking. Small-scale farmers cannot often develop sustainable solutions. Local governments, municipalities, or associations should launch capacity-building programs, including community sensitization, waste transportation, and waste linking to raw materials. The farming community and stakeholders must be educated on waste management to challenge generational thinking and offer technical and socioeconomic assistance. Emphasizing compost usage and recovery programs can lower agrochemical costs and generate additional revenue.

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Index

Note: Page numbers followed by *f* indicate figures and *t* indicate tables.

A

Acetogenesis, 234
Acid digestion, 289
Acidogenesis, 234
Aerated static pile composting, 499
Aerobic composting, 499
Agricultural bio-inputs, 294–295
  bioactive compounds, 294
  bio-fertilizers, 294
  bio-pesticides, 294
  plant bio-stimulants, 295
  protein hydrolysates, 294–295
  soil amendment, 294
Agricultural waste, 21, 49–58, 123–124, 124f, 131, 164, 167–176, 168f, 283–297, 284f, 333–344, 334f, 432, 433f, 155–164
  agricultural residue, 162–163
  agro-industrial byproducts, 170
  applications, 294–296
    bio-inputs, 294–295
    value-added applications, 295–296
  benign industrial products, 254–257
    bio-composites, 256
    biodegradable plastic, 257
    bioenergy potential, 258, 259t–260t
    biomedical material, 254–255
    bioprotein, 256
    bio-stimulants and bio-fertilizer, 255–256
  bioplastics and biofibers, 431–438, 433f
    benefits, 432
    conventional materials, 433, 433t
  challenges and limitations, 296–297, 435–436
    compatibility and performance requirements, 436
    economic and regulatory barriers, 297
    technical challenges, 296–297
    variability, 435, 436t
  chemical conversion mechanisms, 434–435
    lignocellulosic biomass pretreatment, 434
    polymer formation, 434–435
    polysaccharide extraction and purification, 434
  cost and scalability, 436
    challenges, 436
  definition and types, 432
  ecosystem, 160–162, 161t
  environmental impact, 126–128, 171, 432, 437
    biodiversity, 127
    life cycle analyses, 437
    methane emissions, 126–127
    soil and water pollution, 126
environmental pollution, 334–335
  classification, 334–335
fertilizer and plastic use, 50–58, 50t–51t
food spoilage, 170
greenhouse gas emission, 163, 342–344
  carbon sequestration, 343
  eco-friendly energy source, 343–344
  solid-state fermentation, 343
human exposure pathways, 170
  direct exposure, 170
  ingestion, 170–171
  inhalation, 171
human health, 172–176, 172f
  cancer, 174
  cardiovascular dysfunction, 173
  diabetes mellitus, 174–175
  gastrointestinal diseases, 174
  infectious diseases, 175–176
  neurological disorders, 175
  obesity, 175
  ophthalmic discomfort, 173
  reproductive disorders, 173–174
  respiratory obstruction, 172–173
  skin irritation, 173
hydrogen gas production, 341–342
  microbes, 341–342
innovations, SDGs, 257–258
livestock, 169–170
management, 130–131
microalgae cultivation, 335–339, 337t
nutrient extraction techniques, 288–290, 296
  biological methods, 290
  chemical methods, 289–290
  physical methods, 288–289
nutrient, fertilizer, and plastic waste, 52–57
  management, 55–57
  mismanagement reasons, 55
  problems, 54–55, 57
  reason, 54
  sources, 52–53, 53f
nutrient recovery technologies, 290–294
  liquid fractions, 291
nutrient source, 285–288
  bioactive compounds, 288
  nutrient composition, 286–288
  organic matter content, 288
  potential sources, 285–286
pesticides and fertilizers, 169, 169f
  policy implications and knowledge gaps, 163
  quantification and availability, 432
  resource, 125–126
    global distribution, 125
    types and source, 125–126
  soil degradation, 162
  soil faunal diversity, 162
  solutions and research, 437–438
    blending approaches, 437
    cost-effective technologies, 437
    energy-efficient conversion technologies, 437
    formulation optimization, 437
    life cycle analyses, 438
    processing technologies, 437
    standardization and characterization methods, 437
  sources, 156–160, 157f
    fertilizer and pesticides, 156–158
  strategies, 124–125, 128–129
  valorization, 335–339
  value-added products, 253–261, 254f
  waste and its classification, 51–52, 52f
    agro-industrial waste, 52
    crop/harvest waste, 51–52
    hazardous wastes, 52
    livestock wastes, 52
  waste reduction technology, 129
  waste to wealth, 57–58
Agricultural waste biomass, pretreatment
  biological pretreatment, 237
  chemical pretreatment, 236–237
    acid, 236
    alkaline, 236
    organic solvents, 237
    oxidative, 236–237
  physical pretreatment, 235–236
    mechanical, 235
    microwave, 236
    thermal, 236
    ultrasonic, 235
  physicochemical pretreatment, 237–238
Agricultural waste management, 58, 101–117, 130–131, 163–164, 183–198, 212, 307–325, 467–474, 477–488, 493–507
  advancements and opportunities, 487–488
  biotechnologies, 321–324
  challenges and opportunity, 113–116, 324, 486–487, 507
  circular economy, 494–501

Agricultural waste management (*Continued*)
agro-residues, 494–498
organic fertilizer production, methods, 498–500
reinforcement material production, 500–501
comparative analysis, 102–104
ecological footprints, 103–104
farming methods, 102–103
traditional *vs.* sustainable agriculture, 102
critical challenges, 190–192
climate change resilience, 191
cross-sector collaboration, 191–192
environmental impact, 191
environmental impact and sustainability, 192
resource efficiency, 190–191
ecological footprint calculation, 111–112
economic impacts, 205–206
environmental and economic impacts, 480–483
crop burning, 481–482
crop residue effects, 482
livestock manure, 483
pesticide and fertilizer residues, 483
pesticide residue, 481
environmental impacts, 205–206
agricultural plastics, 205
crop residues, 205, 205t
food processing waste, 206
livestock manure, 205
enzymes, 130
food and environment, 308–310
advanced technology, 309
agriculture production and global population, 309
environment ecology, 309–310
functional foods and bioactive compounds, 130, 130t
greenhouse gas emissions, 105f, 106–111, 107t
innovative technologies and approaches, 487
integrated waste management, 470–472
limitations, 192–195
accessibility and affordability, 193
cost constraints, 192
environmental impact, 194
maintenance challenges, 194
social acceptance, 194–195
technology complexity, 193
traditional practices integration, 193
management and utilization, 313–316
bio-fertilizer, 315
carbon source, 314–315
chemicals and fuels, 315
energy generation, 314
food/feed ingredients, 313–314
pigments, 315
secondary metabolites, 315–316, 316t–317t
transforming agricultural waste, 313–316, 314f
microbial biotechnology, 501–506
antibiotic resistance, 505–506
biofertilizer development, 502, 502t, 503f, 503t
biosensors and smart labeling, 505
fiber extraction, 501–502
microbe-mediated augmentation, 503–504
multidrug resistance, 505–506
pathogen detection, 504–505
modern agriculture, 188–190
biological approaches, 190
conventional challenges, 188
emerging technologies, 189
environmental and economic impacts, 189–190
information technology integration, 189
integration, 195–196
limitations, 192–195
traditional practices, 188
nanomaterials, 130
policies and regulations, 472–474
pollution, 104–106
research and best practices, 472
sources and characteristics, 310–311
categories, 310–311
chemical characterization, 311, 312t
strategies, 468–470
emerging innovative technologies, 468–470
technological innovations, 112–113, 131, 197–198
bioenergy production, 197
crop residue management, 197
decomposition, biological approaches, 197
gaps and opportunities, 113
government policies, 198
robotics and automation, 198
traditional agriculture, 184–188
challenges and adaptations, 188
community-based, 186
crop rotation systems, 185
cultural and indigenous perspectives, 187–188
integration, 195–196
natural pest control, 187
post-harvest waste reduction, 187
soil improvement, 185–186
storage and preservation techniques, 186–187
water management, 184
types and sources, 478–480, 478f
agro-industrial residues, 479–480
horticulture and crop production solid waste, 480
livestock manure, 479
post-harvest, 479
valorization, 506–507
aquaculture, 506
livestock and poultry feed, 506
probiotic propagation, 506–507
value-added products, SDGs, 318–321, 319f
income generation options, 319–320
waste management strategies, 483–486, 484f
anaerobic digestion, 485–486
bioenergy generation, 486
composting and vermicomposting, 484–485
waste to wealth conversion, strategies, 317–318
advanced approach, 318
conventional approach, 317–318
Agricultural wastewater, 285
Agriculture waste pollution, 104–106
ecosystem and biodiversity, 105–106, 105f
quantifying types and volumes, 104–105
soil and water quality, 106
types, 104
Agrochemicals, 42, 126
Agro-industrial byproducts (AIBPs), 375–402
animal diets application, 376–398, 376f
apple pomace, 376–378, 377t
citrus pulp, 378–382, 379t–381t
grape pomace, 382–385, 383t–384t
olive cake, 385–388, 386t–387t
others, 398, 399t–401t
palm kernel cake, 391, 392t
pomegranate pulp, 388–391, 389t–390t
sugar beet pulp, 391–395, 393t–394t
tomato pomace, 395–398, 396t–397t
potential limitations, 398–402
Agro-industrial waste, 52
Agro-residues, 451, 452f, 494–498
biochar production, 495
energy production, 495–496
feed production, 496
mushroom and other fungi production, 496
organic fertilizer production, 494
soil fertility, 495
Agro-waste innovations, 257–258
affordable and clean energy, 257–258
clean water, 257
Air quality, 28
Alcohol ethoxylates (AEOs), 39
Algal biomass, 338–339
animal feed, 338–339
bioenergy production, 338
bio-fertilizer, 338
Alkaline pretreatment, 236
Alkylamine ethoxylates (ANEOs), 39
Alkylphenol ethoxylates (APEOs), 39
Anaerobic batch reactor (ASBR), 238
Anaerobic digestion (AD), 207, 215–226, 232–234, 234f, 292, 451, 452f, 469, 485–486, 500
acetogenesis, 234
acidogenesis, 234
biogas production process, 233
methanogenesis, 234
Animal-derived processing waste (ABPs), 63–65
bone waste, 63–65
fishing and aquaculture, 63–65
Animal-derived waste, 68–70
biodiesel production, 70

biofuel production, 70
gelatin biopolymers production, 69
hyaluronic acid, 70
keratin biopolymers production, 69
peptides production, 69–70
protein hydrolysate, 69–70
rendering, 68–69
Animal waste, soil contamination, 127
Antibiotic resistance (AR), 505–506
Apple pomace (AP), 376–378, 377t
Aquaculture, 63–65, 286, 506
Aquatic ecosystem, 160–162
Arthropods, 499–500
Artificial intelligence (AI), 93, 470
Automated cultivation processes, 453–455
Azoxystrobin, 42

B

Bacteria, 30
Bagasse, 10
Bioactive compounds, 294
Bio-alcohol production, 71
Bio-bricks, 501
Biochar, 128–129, 468–469
carbon sequestration, 420–421, 420t
production, 415–426, 495
properties, 418–419, 419t
soil improvement, 421–425
biological properties, 424–425
chemical properties, 422–424, 423t
nutrient availability, 424
physical properties, 421–422, 421t
waste, 416–417, 417f
Biochemical biomarkers, 146
Biochemical conversion, 232–233
Biochemical oxygen demand (BOD), 24
Bio-coal production, 495–496
Bio-composites, 256, 500
Biodegradable plastic, 257
Biodegradable waste, 62
Biodiesel, 31
Biodiesel production, 70
Biodiversity, 310
Bioenergy generation, 486
Bioenergy potential, 258, 259t–260t
Bioenergy production, 67, 129
Bioethanol, 495–496
Bioethanol production, 220–221
Bio-fertilizers, 255–256, 294, 315, 502, 502t, 503f, 503t
Biofuel
biodiesel, 31
biogas, 31
Biofuel production, 70, 220–221
bioethanol production, 220–221
butanol production, 221
methane production, 221–224
Biogas, 31, 233, 469
agricultural waste biomass, 234–238
challenges and opportunities, 248–249
production, 233–238, 245–246, 246f–247f
Bio-hydrogen production, 71
Biological methods, 469
Biological oxygen demand (BOD), 27, 365
Biological pretreatment, 237
Biological soil amendments of animal origin (BSAAO), 30
Biological treatment methods, 206–207
anaerobic digestion, 207
composting, 206, 206f
Biomarkers
biochemical, 146
cytological and genotoxic, 147
hematological, 143
histopathological, 146–147
immunological, 147
omics, 148
oxidative stress, 147
physiological, 147
reproductive, 147–148
Biomaterials production
bioplastic production, 72–73
enzymes recovery, 73
Biomedical material, 254–255
Bio-methane production, 70–71
Bio-oil, 295
Bio-oxidation process, 32
Biopesticides, 38
Bio-pesticides, 294
Bioplastic, 500–501
Bio-polymers, 296
Bioprotein, 256
Biorefineries technology, 470, 471t
Bioremediation, 57
Biosensors, 505
Bio-sorbents, 295
Bio-stimulants, 255–256
Biosurfactants, 323
Biotechnologies, 321–324
Black soldier fly (BSF), 33
Blockchain, 470
Bone waste, 63–65
bran, 7–8
Bulky organic amendments, 292
Butanol production, 221
Byproducts, 3–5, 7–10, 13, 125–126
bagasse, 10
bran, 7–8
husks, 9
pomaces, 9
press cake, 9
pulp, 10
spent grain, 10

C

Cancer, 174
Capacity building, 196
Cardiovascular dysfunction, 173
Cation exchange capacity (CEC), 423
Cattle and buffaloes, 22
Cereal crops waste, 310–311
Chelation, 290
Chemical conversion mechanisms, 434–435
lignocellulosic biomass pretreatment, 434
polymer formation, 434–435
polysaccharide extraction and purification, 434
Chemical oxygen demand (COD), 24, 365
Chemical precipitation, 210–211, 290
Chemical pretreatment, 236–237
acid, 236
oxidative, 236–237
Chemical treatment methods, 207–208
hydrolysis, 208
oxidation, 208
solvent extraction, 208
Circular economy (CE), 66, 319, 470, 494–501
Citrus pulp (CP), 378–382
Closed bioreactor, 336–337
Co-composting, 499
Common property resources (CPR), 23
Comparative analysis, 102–104
ecological footprints, 103–104
farming methods, 102–103
traditional *vs.* sustainable agriculture, 102
Compositing, 128, 206f, 291, 469, 484–485
Confined animal feeding operations (CAFOs), 21
Continuous flow stirred tank reactors (CSTR), 239
Conventional agro-waste management, 318
Cost-effective analysis, 324
Crop/harvest waste, 51–52
Crop management, 131
Cropping, 447–448
Crop production solid waste, 480
Crop residues, 3–7, 13, 125, 128, 285
husks and hulls, 6
leaves, 6
pruning and trimmings, 7, 8t
root systems, 7
stems and stalks, 5–6
stover, 7
straw, 6
Cypermethrin, 141
Cytological biomarkers, 147

D

Dark fermentation, 220
Depression, 175
Diabetes mellitus, 174–175
Drip irrigation, 80
Dung/animal excreta, 22–24
cattle and buffaloes, 22
pigs and poultry, 23–24
sheep and goats, 23

E

Ecological footprint (EF), 81
Economic viablility, 195–196
Electro-dialysis, 289
Elemental composition, 65
Emerging innovative technologies, 468–470
Energy generation, 314
Energy production, 495–496
Environmental impact assessment (EIA), 195
Environment ecology, 309–310
Enzymatic hydrolysis, 290

F

Feed production, 496
Fermentation, 209–210
Fertilizers, 127, 156–158, 169, 169f, 270
Fiber extraction, 501–502
Fishing, 63–65
Floriculture-derived byproducts, 286
Food processing byproducts, 285–286
Food processing waste, 61–74, 206
  animal-derived, 63–65
    bone waste, 63–65
  characterization, 65–66
    elemental composition, 65
    functional groups, 65–66
    thermal biodegradability, 65
  management and reduction, 66
  recycling, 66–67
    bioenergy production, 67
    vermicomposting, 67
  source, 62–63
  valorization, 68–73
    animal-derived waste, 68–70
Food safety, 82, 320
Food supply, 308
Food waste (FW), 62, 320
Fourier transform infrared (FTIR) spectroscopy, 65–66
Freshwater fish, 143–148, 144t–145t
Freshwater invertebrates, 140–143
Freshwater molluscs, 141–143
Fruit wastes, 451
Fungicides, 42
Fungi production, 496

G

Gastrointestinal diseases, 174
Gelatin biopolymers production, 69
Genetically modified organisms (GMOs), 159–160
Genetic engineering, 323
Genotoxic biomarkers, 147
Geographic information system (GIS), 112
Global agriculture sector, 79–94
  ecological footprints and agriculture, 81–82
    impacts, 81
    strategies, 82
  water footprints, 80–81
    economic implications and global significance, 80
    intrinsic value, 80
    research, 80–81
  water scarcity, 82–83
    approaches, 83, 83f
    causes and consequences, 82
    food security, biodiversity, and livelihoods, 82
Global food production, 84–85
Global positioning systems (GPS), 92–93
Grape pomace (GP), 382–385, 383t–384t
Gray water footprint (GWF), 87
Green construction materials, 129
Green energy, 295
Greenhouse gases (GHG), 28, 105f, 106–111, 107t, 109t, 110f, 111t, 342–344

H

Harvest
  byproducts, 7–10, 13
    bagasse, 10
    bran, 7–8
    husks, 9
    pomaces, 9
    press cake, 9
    pulp, 10
    spent grain, 10
  challenges and opportunities, 12–13, 12f
  crop residues, diverse forms, 5–7, 13
    husks and hulls, 6
    leaves, 6
    pruning and trimmings, 7, 8t
    root systems, 7
    stems and stalks, 5–6
    stover, 7
    straw, 6
  definition, 3–13, 4t
  origin and composition, 4–5, 5t
  utilization and benefits, 10–12, 11f
Hazardous wastes, 52
Hematological biomarkers, 143
Hepatitis E virus (HEV), 31
Herbicides, 42, 127
Histopathological biomarkers, 146–147
Horticultural waste, 311
Horticulture, 480
Hulls, 6
Human pathogenic bacteria (HPB), 30
Husks, 6, 9
Hyaluronic acid (HA), 70
Hydrogenases, 219
Hydrogen gas production
  microbes, 341–342
    agricultural waste, 342
    carbon sequestration, 343
    eco-friendly energy source, 343–344
    fermentation conditions, 342
    reactor design, 342
    solid-state fermentation, 343
    strain screening, 341–342
Hydrogen production, 218–219
Hydrolysis, 208
Hydroponic mushroom farming, 453–454

I

Immunological biomarkers, 147
Incineration, 212
Infectious diseases, 175–176
Information and communication technology (ICT), 92–93
Insecticides, 42
In situ decomposition, 291
Integrated pest management (IPM), 43
Integrated waste management (IWM), 470–472
Integrated waste management systems (IWMS), 203–212
  biological treatment methods, 206–207
    anaerobic digestion, 207
    composting, 206, 206f
  chemical precipitation, 210–211
  chemical treatment methods, 207–208
    hydrolysis, 208
    oxidation, 208
    solvent extraction, 208
  combined and integrated approaches, 208–210
    environmental and economic considerations, 208–209
    fermentation, 209–210
  importance, 204, 204f
  physical treatment methods, 211–212
    incineration, 212
    landfilling, 211–212
    pyrolysis, 211
Integrated water resources management (IWRM), 91
In-vessel composting, 499
IoT-enabled automated systems/hybrid cultivation systems, 455

K

Keratin biopolymers production, 69
Knowledge transfer, 196

L

Landfill waste treatment, 56–57, 211–212, 292
Lautering, 10
Leaves, 6
LECO analysis, 65
Life cycle assessment (LCA), 111–112, 437–438, 472
Lignocellulosic biomass pretreatment, 434
Liquid formulations, 292–294, 293t
Livestock feed, 296
Livestock production, 22, 23t
Livestock waste, 21–33, 52, 285
  environment, 27–29
    air quality, 28
    greenhouse gases, 28
    human and animal health, 28
    soil quality, 27–28
    water quality, 27
  management, 24
  odors, 29–30
    additives, 29
    implications, 29
    nutritional management strategies, 29–30
    sources, 29
  pathogens, 30–31
    microbes, 30–31
  production, 22–27
    characteristics, 25–27, 26t
    economic considerations, 24–25
    livestock processing systems, 24

livestock species, 22–24, 23f
utilization, 31–33
animal feed, 32–33
biofuel, 31
biodiesel, 31
biogas, 31
organic fertilizer, 31–32
composting, 32, 32f
vermicomposting, 32

M

Mechanical pretreatment, 235
Mechanical separation, 289
Membrane distillation, 289
Membrane filtration, 289
Metabolic engineering, 323
Methane production, 221–224
Methanogenesis, 222–224, 223f, 225t, 234
Microalgae cultivation, 335–339
algal biomass, 338–339
nutrient recovery, 336
reactors, 336–337
closed bioreactor, 336–337
open pond system, 336
Microbe-mediated augmentation, 503–504
Microbial biotechnology, 501–506
antibiotic resistance, 505–506
biofertilizer development, 502, 502t, 503f, 503t
biosensors and smart labeling, 505
fiber extraction, 501–502
microbe-mediated augmentation, 503–504
multidrug resistance, 505–506
pathogen detection, 504–505
Microbial decomposition, 218–220
Microbial degradation, 290
Microbial electrolysis cell (MEC), 220
Microbial strains, 323
Microwave-assisted pyrolysis (MAP), 289, 468–469
Microwave pretreatment, 236
Multidrug resistance (MDR), 505–506
Mushroom cultivation methods, 452–453
automated cultivation processes, 453–455
composted substrates, 452–453
enzymes, 453
hydroponic mushroom farming, 453–454
pros and cons, 454
IoT-enabled automated systems/hybrid cultivation systems, 455
non-composted substrates, 452
smart farming technologies, 453–455
solar-powered cultivation systems, 454
vertical farming system, 453–454
Mushroom production, 444–448, 496
cropping, 447–448
culture (spawn) production, 444, 444f
mother spawn preparation, 445, 445f, 445t
pinning, 447
spawn production/spawn multiplication, 446, 446f
spawn run, colonization, 447
substrate (spawning), inoculation, 447
substrate preparation, 445
substrate (compost) production, 446–447
Mushrooms, 443–461
agro-waste substrates, 451–453
cultivation methods, 452–453
residue biomass, global availability and estimates, 451
sources, 451–452
cultivation and types, biology, 444–450
common lignocellulosic, 448–450, 448f, 449t
mushroom production process, 444–448, 444f
spent mushroom substrate, 455–460

N

Nano-fertilizers, 39–40, 39f
Nanoparticles (NP), 222–224, 223f, 225t, 271–272, 272t–273t
challenges, 275
mechanisms, 274–275
potentiality, 272–274, 273t
Nano-pesticides, 39–40, 39f
Nanotechnology, 267–275, 323
agriculture, 268–270, 269f
fertilizers, 270
pesticides, 268–269
nanoparticles, 271–274, 272t–273t
strategies, 270–271, 271f
Natural fibers, 296
Neurological disorders, 175
Nitrogenases, 219
Nutrient composition, 286–288
beneficial nutrients, 288
micronutrients, 288
primary macronutrients, 286, 286t–287t
secondary macronutrients, 286t–287t, 288
Nutrient extraction techniques, 288–290
biological methods, 290
chemical methods, 289–290
physical methods, 288–289
Nutrient, fertilizer, and plastic waste, 52–57
management, 55–57
bioremediation, 57
clay minerals use, 56
landfills, 56–57
pyrolysis, 57
technique, 55–56
mismanagement reasons, 55
problems, 54–55, 57
reason, 54
sources, 52–53, 53f
Nutrient recovery technologies, 290–294
Indian traditional knowledge, 292–294
bulky organic amendments, 292
liquid formulations, 292–294, 293t
liquid fractions, 291
ammonium recovery, 291
struvite precipitation, 291
solid-phase nutrient recovery, 291–292
anaerobic digestate, 292
composting, 291
landfill waste treatment, 292
pyrolysis, 292
in situ decomposition, 291
Nutritional management strategies, 29–30

O

Obesity, 175
Olive cake (OC), 385–388, 386t–387t
Omics biomarkers, 148
Open pond system, 336
Ophthalmic discomfort, 173
Organic fertilizer, 31–32
Organic fertilizer production, 494
Oxidation, 208
Oxidative pretreatment, 236–237
Oxidative stress biomarkers, 147

P

Palm kernel cake (PKC), 391, 392t
Parasites, 30–31
Pathogens, 30–31, 504–505
Pesticides, 37–44, 127, 156–158, 169, 169f, 268–269
agricultural chemicals, 40, 41f
agro-industrial wastes, 159
aquatic ecosystem, 160–162
environmental impact and ecological consequences, 39f, 40–43
agricultural chemicals, mechanisms, 42–43
insecticides, herbicides, and fungicides, mechanisms, 40–42
genetically modified organisms, 159–160
nano-fertilizers, 39–40, 39f
limitations, 40
organic waste, 158–159
sources, 38–39, 38f
technological advances, 43–44
impact, 44
innovations, 43–44
terrestrial ecosystem, 160
Photofermentation, 219–220
Physical pretreatment, 235–236, 235f
Physicochemical pretreatment, 237–238
Physiological biomarkers, 147
Pigments, 315
Pigs and poultry, 23–24
Pinning, 447
Plant bio-stimulants, 295
Plant-derived waste, 70–71
bio-alcohol production, 71
biofuel production, 70
bio-hydrogen production, 71
bio-methane production, 70–71
Plant-disease management, 456
Plastic waste
alternative approach, 57
incineration, 56
recycling, 56
Pollution water indicator (PWI), 88
Polymer formation, 434–435
cellulose-based bioplastics, 434
hemicellulose-based bioplastics, 434
PHA production, 434–435

Polysaccharide extraction and purification, 434
Pomaces, 9
Pomegranate pulp (PP), 388–391, 389t–390t
Post-harvest and processing waste, 311
Precision agriculture technology, 469
press cake, 9
Primary macronutrients, 286, 286t–287t
Process residues, 3
Protein hydrolysates, 294–295
Protozoa, 30–31
Pruning, 7, 8t
Pulp, 10
Pyrethroids, 137–148, 142t–143t
  behavioral biomarkers
    biochemical, 146
    cytological and genotoxic, 147
    hematological, 143
    histopathological, 146–147
    immunological, 147
    omics, 148
    oxidative stress, 147
    physiological, 147
    reproductive, 147–148
  evolution, 138
    action modes, 138–139
    uses, 138, 139t–140t
    water bodies, 139–140, 141f
  freshwater invertebrates, 140–143
    freshwater fish, 143–148, 144t–145t, 146f
    tadpoles, 143, 143t
  scopes, 148
Pyrolysis, 57, 211, 292

R

Radio-frequency identification (RFID), 505
Recycled nanomaterials (RNMs), 254–255
Rendering, 68–69
Reproductive biomarker, 147–148
Rice cultivation, 80–81
Robotic technologies, 92–93
Root systems, 7

S

Salinization, 127–128
Secondary macronutrients, 286t–287t, 288
Secondary metabolites, 315–316
Sheep and goats, 23
Size reduction technologies, 289
Skin irritation, 173
Smart agricultural machinery system (SAMS), 93
Smart farming technologies, 453–455
Smart labeling, 505
Smart waste disposal technology, 470
Soil acidification, 127–128
Soil amendment, 294
Soil conservation
  agriculture waste, 123–124, 124f
    strategies, 124–125
Soil contamination, 127
Soil degradation, 128, 162
  strategies, 128–129
    agricultural practices, 128–129
Soil enzymatic activity, 425
Soil faunal diversity, 162
Soil fertility, 495
Soil health, 121–131, 122f–123f, 309–310
  agricultural activities, impact, 123, 123t, 127–128
  agricultural waste, impact, 124
    crop residues, 128
    soil acidification and salinization, 127–128
    soil contamination, 127
    soil degradation, 128
Soil microbial community, 424–425
Soil quality, 27–28
Solid-state fermentation, 339–341, 343
  crop waste, 339–341
  high-value microorganisms, 340–341
Solid-state fermentation (SSF), 323
Solvent extraction, 208, 290
Spawning, 447
Spawn run, 447
Spent grain, 10
Spent mushroom substrate, 455–460
  casing material, 456
  cultivation, 455–456
  nutritional value and secondary metabolites production, 457
  plant-disease management, 456
  soil conditioner and bio-fertilizer, 456
  valorization, 457–460, 458f, 459t–460t
Stalks, 5–6
Stems, 5–6
Stover, 7
Straw, 6
Struvite precipitation, 291
Sugar beet pulp (SBP), 391–395, 393t–394t
Sustainable development goals (SDGs), 257–258, 284, 318–321, 431
Synergies, 196

T

Tadpoles, 143, 143t
Technological integration, 196
Terrestrial ecosystem, 160
Thermal biodegradability, 65
Thermal pretreatment, 236
Time-temperature indicators (TTIs), 505
Tomato pomace (TP), 395–398, 396t–397t
Total ammoniacal nitrogen (TAN), 65
Total solids (TS), 65
Total suspended solids (TSS), 24, 365
Traceability, 470
Traditional composting, 498
Transformed products (TPs), 38
Trimmings, 7, 8t

U

Ultrasonic pretreatment, 235

V

Valorization, 68–73, 218–220, 335–339, 506–507
  animal-derived waste, 68–70
    biodiesel production, 70
    biofuel production, 70
    gelatin biopolymers production, 69
    hyaluronic acid, 70
    keratin biopolymers production, 69
    peptides production, 69–70
    protein hydrolysate, 69–70
    rendering, 68–69
  aquaculture, 506
  biomaterials production, 72–73
    bioplastic production, 72–73
    enzymes recovery, 73
  challenges and perspectives, 224–226
  dark fermentation, 220
  hydrogenases, 219
  hydrogen production, 218–219
  livestock and poultry feed, 506
  microbial electrolysis cell, 220
  nitrogenases, 219
  photofermentation, 219–220
  plant-derived waste, 70–71
    bio-alcohol production, 71
    biofuel production, 70
    bio-hydrogen production, 71
    bio-methane production, 70–71
  probiotic propagation, 506–507
  value-added components, 71–72
    bio-adsorbents, 72
Value-added products, 129
Vegetable wastes, 451
Vermicomposting, 32, 67, 349–367, 350f, 484–485, 499
  advancements and opportunities, 365–366
    emerging trends, 365–366
    research needs and knowledge gaps, 365–366
  bedding materials, 352
  benefits, 357–358
    environmental benefits, 357
    nutrient recycling and carbon sequestration, 357–358
    soil health and fertility enhancement, 357
  challenges, 360–362
    quality, 361–362
    regulations and standards, 360–361
    scalability and operational, 360
  earthworms, 351
  economic considerations, 362–363
    cost-benefit analysis, 362
    financial viability and economic sustainability, 363
    market potential, 362
  environmental impact, 352–353
  key components, 351
  organic feedstock, 352
  quality factors, 353–356, 354t
    additives, 354–355
    duration and process, 355–356
    earthworm species, 353–354
    fertilizers, 356

microbial inoculants, 355
raw materials, 353
soil properties, 356
temperature, 354
risks, 358–360
contamination risks, 358–359
odor issues, 359
pathogen presence, 359–360
strategies, 363–365
best practices, 363–364
policy recommendations and supportive initiatives, 364–365
technological innovations and advances, 364
worm bins, 352
Vertical farming system, 453–454
Viruses, 31
Volatile fatty acids (VFA), 238
Volatile solids (VS), 65

W

Waste biodegradation, 221–224
Waste biomass, 130–131
Waste-derived catalysts, 295–296
Waste digestion, 221–224
Waste energetic valorization, 224–226
Waste management, 43–44
anaerobic digestion, 215–226
biofuel production, 220–221
bioethanol production, 220–221
butanol production, 221
bioremediation, 218
definition and principles, 218
mechanisms, 218
classification, 51–52, 52f
agro-industrial waste, 52
crop/harvest waste, 51–52
hazardous wastes, 52
livestock wastes, 52
limitations, 192–195
accessibility and affordability, 193
cost constraints, 192
environmental impact, 194
maintenance challenges, 194
social acceptance, 194–195
technology complexity, 193
traditional practices integration, 193
methane production, 221–224
methanogenesis performance, nanoparticles role, 222–224, 225t
modern agriculture, 188–190
biological approaches, 190
conventional challenges, 188
emerging technologies, 189
environmental and economic impacts, 189–190
information technology integration, 189
integration, 195–196
limitations, 192–195
traditional practices, 188
technologies, 183–198
critical challenges, 190–192
traditional agriculture, 184–188
challenges and adaptations, 188
community-based, 186
crop rotation systems, 185
cultural and indigenous perspectives, 187–188
integration, 195–196
natural pest control, 187
post-harvest waste reduction, 187
soil improvement, 185–186
storage and preservation techniques, 186–187
water management, 184
valorization, 218–220
dark fermentation, 220
hydrogenases and nitrogenases, 219
hydrogen production, 218–219
microbial electrolysis cell, 220
photofermentation, 219–220
waste types, 217, 217t
Waste management technologies, 183–198
critical challenges, 190–192
climate change resilience, 191
cross-sector collaboration, 191–192
environmental impact, 191–192
resource efficiency, 190–191
sustainability, 192
Waste-to-energy technologies, 231–249, 469
agricultural waste biomass, pretreatment, 234–238
physical pretreatment, 235–236, 235f
anaerobic digestion, 233–234
acetogenesis, 234
acidogenesis, 234
biogas production process, 233
hydrolysis, 233
methanogenesis, 234
anaerobic digestion biogas production process, 233–234
biochemical conversion, 232–233
biogas applications, 244–245
biogas benefits and limitations, 246–248
biogas production factors, 239–241
biogas upgrading, 241–244
operational methods and reactor designs, 238–239
Waste treatment technologies, 43–44
Wastewater treatment, 131
Water availability footprint (WAF), 87
Water degradation footprint (WDF), 87–88
Water footprint (WF), 83–84, 92–93
agricultural productions, 85–86
definitions and components, 83–84
factors, 90–92, 90f, 91t
global food production, 84–85
methodologies and tools, 86–90
precision agriculture, role, 92
research, 80–81
drip irrigation, 80
technologies and practices, 92–93
Water quality, 27
Water scarcity, 82–83
approaches, 83
causes and consequences, 82
food security, biodiversity, and livelihoods, 82
Water scarcity footprint (WSF), 88
assessments, 88–90
comparative analysis, 88, 89t
Water use efficiency (WUE), 85
Windrow composting, 498

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