

Second Edition

CLIMATE CHANGE AND AGRICULTURAL ECOSYSTEMS

CURRENT CHALLENGES AND ADAPTATION

Edited by

Ajay Kumar, Olubukola Oluranti Babalola,
Joginder Singh, and Gustavo Santoyo



Climate Change and Agricultural Ecosystems

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Preface

Agricultural ecosystems are highly dependent on weather and climate for the production of necessary foods to sustain human life. Despite leading, cutting-edge tools and technologies for developing improved varieties, genetically modified organisms, and irrigation systems, climate change is still a major constraint for agricultural productivity. Climate variability and weather extremes such as droughts, floods, global warming, and severe storms, which are prime consequences of climate change, will make agriculture more susceptible and difficult for ensuring food security for the ever-expanding global population. Therefore, with the help of contributing experts, this book summarizes the different aspects of vulnerability, adaptation, and amelioration of climate change in respect to plants (crops and medicinal plants), soil, and microbes for the sustainability of the agricultural sector and, ultimately, the issue of food security under futuristic scenarios. This book will also focus on the understanding and utilization of information technology for the sustainability of the agricultural sector along with the capacity and adaptability of agricultural societies under climate changing scenarios. Most importantly, the compiled information within this book will be useful for students, teachers, and researchers at universities and research institutes, especially those working in the study fields of global climate change, environmental sciences, soil sciences, agricultural microbiology, plant pathology, and agronomy.

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The impact of climate change on agricultural ecosystem

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1.1 Introduction

In addition to drought, extreme temperatures, flooding, an increase in pests and plant diseases, and decreased food yields and nutritional quality, the impact of climate change on agriculture may reduce crop yields (Liliane & Charles, 2020). The impacts of climate change make it more difficult for agriculture to provide for the needs of humanity. World change in climate has an inequitable impact on the consequences caused by changes in temperature, precipitation, and atmospheric carbon dioxide levels (Rosenzweig & Liverman, 1992). Due to global warming, millions of people already experienced food insecurity in 2019. Furthermore, a 2%–6% reduction in

world crop productivity is anticipated every 10 years (Pastor, 2019). In 2019, it was expected that by the year 2050, food costs would have increased by 80% (Blok et al., 2021). Poorer populations will likely be disproportionately affected by increasing hunger as a result of this. According to a study conducted in 2021, crop output damages across Europe over the previous 50 years increased by a factor of three, from 2.2% between 1964 and 1990 to 7.3% between 1991 and 2015 (Brás, 2021). Increased humidity, extreme heat, and variations in rainfall (including droughts and floods) are immediate consequences of shifting climate conditions. Because of CO₂ fertilization, greater levels of carbon dioxide in the atmosphere have increased crop yields, but they additionally resulted in decreased crop nutritional content (lower amounts of micronutrients) (Beach, 2019). Decreased yields from agriculture and nutritional value may also be a consequence of changes in pests, plant diseases, and weeds brought on by the climate. A side effect of global warming is the loss of agricultural land owing to sea level rise. But as frozen terrain melts, more agricultural land may become accessible, even though melting glaciers might mean less irrigation water is available (Haeberli & Weingartner, 2020). Additional consequences include fertility of the soil changes, erosion, and lengthened seasons for growth. As the temperature heats, fungi that produce mycotoxins and bacteria like Salmonella cause more harm to food safety and losses, adding to the associated cost pressures (Duchenne-Moutien and Neetoo, 2021). Agriculture may be significantly harmed by shortages of water, which include changes in terrestrial in nature rainfall, evaporation, and soil moisture brought on by or made worse by global warming. Several environmental mitigation measures could lessen the likelihood of adverse effects on agriculture. These solutions comprise adjustments to management procedures, innovations in agriculture, modifications to institutional structures, and climate-smart agriculture. These steps are thought to be just as crucial for developing a food system that is sustainable as the adjustments required to lessen global warming generally (Makate, 2019).

One of the most major problems facing the globe now is climate change. It is described as notable variations in the median values of meteorology variables, including temperature and precipitation, when averages were calculated over an extended amount of time. According to recent decades, increased activity by humans that changed the composition of the Earth's atmosphere led to significant shifts in the worldwide climate (Somani, 2020). Since the year 1750, there has been a 150%, 40%, or 20% rises in the number of greenhouse gases such as methane (CH₄), CO₂, or nitrous oxide (N₂O), etc. (Meena, 2019). The total amount of carbon dioxide emissions, which make up the vast majority of greenhouse gases, increased from 22.15 billion metric tons in 1990 to 36.14 billion metric tons in 2014. Since the year 1975, the worldwide mean temperature has risen annually at 0.15°C–0.20°C per decade; by 2021, the median rise is predicted to reach 1.4–5.8°C (Zignol, 2019). The phenomenon of global warming is a result of releases of greenhouse gases (GHGs), mainly CO₂ from the burning of petroleum and coal and non-CO₂ GHGs such as nitrous oxide, methane, and Chlorofluorocarbons (CFCs). Based on 315.98 ppm in the year 1959 for 411.43 ppm in the year 2019 the atmospheric CO₂ concentration has increased (Jiang et al., 2018). CO₂ makes up a significant portion of greenhouse gas emissions, contributing 65% from petroleum and natural gas and manufacturing activities and 11% from forestry as well as other land uses.

This is followed by methane (16%), nitrogen oxides (6%), and fluorine gases (2%). Before 1750, carbon dioxide emissions from fossil fuels were minimal, but industrialization caused them to rise quickly (Ussiri & Lal, 2012). Since the number of people has increased over history, a wide range of modifications to daily living, society, technological research, economic activity, and crop production have also taken place. Agriculture has also gone through many significant shifts as a result of agricultural revolutions, which were also affected by the expansion of society, innovation, and humankind in general (Barrett, 2021). However the staggering rate of increase in population over the past century has resulted in several unfavorable effects; it, coupled with modifications to the environment, will affect the availability of food supplies. For humanity to satisfy the increased dietary requirements brought by the growing population, worldwide farming output would most certainly be required to triple by the decade of 2050 as well (Molotoks et al., 2021). Multiple research studies indicate that increasing agricultural output, as opposed to developing additional land areas for cultivation, is the best and most viable option for ensuring the security of food. The effects of climate change along with associated phenomena, such as increasing temperatures worldwide and levels of carbon dioxide in the atmosphere, soaring temperatures, water damage, violent thunderstorms, severe droughts, and various other extreme conditions are the subject of current scientific investigation and agricultural science (Agache, 2022). So when the propensity for decreasing the loss of yield owing to such conditions develops, greater focus is placed on the abiotic variables stated above in research into agriculture. Variations in the amount of precipitation could possibly be more significant for crop production than temperature increases, particularly for regions whose dry seasons pose a barrier to agricultural output (Nkwi, 2023). Pests are a significant biotic element that is additionally affected by warming temperatures and changes in the weather. The development, survival, dissemination, and demographics of pests in addition to the interactions among insects, surroundings, and other organisms are all significantly affected by temperature change (Skendžić, 2021). As a result, it is crucial to keep an eye on pests' presence and quantity because the circumstances around where they happen might rapidly alter. Particularly, this section will look at how increasing temperatures as well as outside carbon dioxide concentrations of substances, as well as variable patterns of precipitation, have an impact on both the ecology and the biology of damaging pests, particularly incurable pest species, that may be a serious threat to agricultural output (Chouvalova, 2023). The presentation of potential remedies for the current problems in plant production will primarily take the shape of improved IPM (integrated pest management) methods, that connect Integrated Pest Management with the cultivation and manufacturing of nutritious foods in a sustainable way as well as methods for monitoring and modeling forecasting methods (Hajjar, 2023).

1.2 Climate change

Hydration or the availability of water, cryology, ocean or freshwater environments, ecosystems on land, forest products, as well agriculture are just a few of the controlled or uncontrolled processes which are heavily influenced by the environment

(Lucas, 2019). This may be defined as an effect that takes place when environmental variables like temperature, humidity, and precipitation fluctuate over an extended amount of time. The production of food worldwide is in grave danger consequently from more extreme climatic extremes, a rise in carbon dioxide along with other greenhouse gases (GHGs), and changed weather patterns (Malhi et al., 2021). The entire world is currently dealing with a significant issue called climate change. As indicated by the exceptional rates of increase in the air temperature or level of the sea, it is nearing unparalleled amounts (Xu, 2021). The entire globe is at present around 50% warmer than it was beforehand due to extensive industrial development, based on data from the World Weather Organization. The last 30 years have gotten warmer overall, according to the report from the Intergovernmental Panel on Climate Change with the early 2000s becoming the warmer century (Fernandez, 2020). During the course of the century that follows, it is predicted that our planet could increase in temperature by 1.5°C–5.7°C because of several climate model projections and human growth predictions. Rising atmospheric levels of atmospheric greenhouse gases are the biggest reason for climate change (Alves de Oliveira et al., 2021). The three kinds of gases that most frequently occur in the atmosphere are CO₂, CH₄, or N₂O. These gases are generated through a variety of activities performed by humans, such as the burning of petroleum and coal and changes in the use of land (Goldstein, 2020). When comparing the period before industrialization with the past 200 years of industrialization, the amount of greenhouse gases has risen significantly. CO₂ is among the most significant or common of the gases that cause global warming. Among the most noticeable worldwide effects on the environment during the last 50 years has been the rise in atmospheric CO₂. Compared with the 280-ppm estimated for the pre-industrial duration, their atmospheric level has risen rapidly, nearly 418 ppm, and it is expected to double in 2100 (Jacobson, 2019). Due to its significant absorption of some heat in the infrared spectrum generated from the Earth's surface, CO₂ is classified as a gas that causes climate change. The percentage of energy released off the upper atmosphere towards the surface of the planet increases with the number of greenhouse gasses that consume thermal infrared rays from the outermost layer of the Earth (Jogdand, 2020).

1.3 Direct effects of weather pattern changes

1.3.1 High weather conditions

Early greenish dryness and Capeweed (*Arctotheca calendula*) infestation in a 2009 barley and wheat crop near Gregadoo, the state of New South Wales, Australia. Locations deemed suitable for farming are going to shift because as a result of weather and temperature fluctuations (McMaster, 1999). Currently, it is predicted that throughout semi-arid and arid areas (also known as the Middle East, Africa, Australia, Southwest United States, and Southern Europe), temperatures will go up and rainfall will decline. Additionally, it is expected that the moderate rise in temperatures (1°C–2°C) anticipated to take place during the initial half of the future will have a detrimental impact on agricultural output in tropical countries

(Lesk, 2021). The yields of crops are expected to decline across the board in the subsequent part of the decade, especially in Canada plus the northern United States. Most typical crops are very heat-sensitive; for example, soybean seedlings die at temperatures above 38°C, or corn pollen becomes lifeless.

Extended seasons of growth might be due to increased wintertime temperatures as well as longer weeks without freezing in some places. For example, a study conducted in 2014 discovered increasing temperatures caused yields of maize in the Heilongjiang region of China to grow from 6% to 16% every 10 years (Liu, 2021).

1.3.2 Heat tolerance in animals

Heat exhaustion impacts the capacity of animals to expand, reproduce, and consume food. This subsequently, in turn, affects both livestock and dairy product output (Abd El-Hack et al., 2020). Heat exhaustion causes a reduction in dietary intake, a slowdown in the level of activity, or a loss of weight. Livestock must have simple access to water and their feeding schedules must be changed to cooler hours of daylight to reverse the reduction in animal productivity. Additionally, a well-ventilated shelter can assist prevent heat exhaustion. The capacity of animals of various kinds to withstand heat stress varies (Ioannou, 2022).

1.3.3 Variations in precipitation, such as droughts and floods

Harvest rate decline is a consequence of drought or flooding. Dried-up conditions may damage harvests or ruin the dietary sources interrupting farming operations or displacing employees if severe storms become more prevalent along with more severe (Parven, 2022). Among underdeveloped nations, heat worsens the already-existing poor or causes hunger and starvation. Using localized chilling, watering from farms may mitigate or entirely mitigate the effects of less precipitation or increased temperatures for output (Liliane & Charles, 2020). However, it is costly as it provides drawbacks to using supplies of water during cultivation. Additionally, the fluid must originate somewhere; if the region in question has experienced extended flooding, the rivers could be drained and it might be necessary to transfer rainfall over more distances. Climate change has increased the frequency of severe weather, which will probably keep increasing throughout the African continent, southern Europe, the Near East, much of the Western Hemisphere, Australia, and the two regions of Asia (Birnie et al., 2022). Additional utilization of water, growing populations, and widespread urbanization all exacerbate the impact they have. Failure of crops and a shortage of land used for animals to graze are two effects of disasters. Some landowners might decide to depart from a drought-stricken location forever and begin farming nearby (Pérez, 2021). Water emergencies in the central part of the USA during the early years of the 20th century likely reduced the time for planting, harming the agricultural industry. Flooding in the month of May 2019 decreased the anticipated harvest of corn to 15 million billion just 15.2 billion. Forecasts indicated that the farming industry of the Belgian nation, one of the nations most severely impacted during the storms, would sustain substantial losses from the 21st century's

European storms, involving a long-term impact such as soil deterioration (Diaconu & Grecu, 2023).

1.3.4 The immediate consequences of higher levels of carbon dioxide in the atmosphere

Because of carbon dioxide fertilization, agricultural products, greenery, or timber yields have increased. Numerous implications for more CO₂ in the atmosphere for crops have been discovered. Increased transpiration rate boosts crop output as development, and closing off reduces transpiration, each of the harmful effects of increased carbon dioxide (Chowdhury, 2021). Although reducing transpiration from foliage, the CO₂ fertilizer impact or carbon enrichment impact speeds up photosynthesis in vegetation. Increasing quantities in the atmosphere of CO₂ causes both reactions. The impact of carbon fertilizer differs based on the type of plants, their ambient temperature available, the environment and the soil, and the accessibility of nutrients as well as water (Elkhlifi, 2023). The carbon dioxide enrichment impact may have a favorable impact on net agricultural output. Research does, however, indicate the greater levels of photosynthesis in plants brought by fertilization with CO₂ are unlikely to boost total crop development as well as consequently, the accumulation of carbon (Sinclair et al., 2019). During the year 2000, there has apparently been a 44% rise in net basic output, which is believed to be attributed to the carbon fertilizer impact. To evaluate and understand shifts in vegetation associated with rising CO₂ levels in the atmosphere, unpredictable worldwide vegetative designs, agricultural system models, and planetary system simulations have been utilized (D'Croz et al., 2022). However, it is difficult to simulate environmental activities connected to the fertilizer's CO₂ effect because the details are still unknown. Coastal ecosystems have lowered the amount of CO₂ in the atmosphere while helping to offset the consequences of climate change. Because of the growing human impact on CO₂ in the atmosphere, it seems doubtful that vegetation responses to their carbon enrichment impact will considerably lower the amount of CO₂ in the atmosphere over the next 100 years. Since the beginning of 1981, the planet's landscapes have significantly greened, mainly as a result of growing atmospheric CO₂ (Yuan, 2019).

1.4 Indirect effects of global warming on diseases, pests, or herbicides

Additional details: invading plants and animals, invading organisms, or environments are all impacted by warming temperatures. the geographic distribution of pests, plant diseases, and weeds will change due to warming temperatures, which might lead to a decrease in agricultural profits, especially those of essential crops such as corn, wheat, or soybeans (Shahzad, 2021).

1.4.1 Insects and pest

Viral infections already consume 11%–15% of the world's pick, but this percentage will continue to increase when plants are exposed to pests and diseases more frequently. Pests groups' energy expenditure as well as the amount of cycles of reproduction may go up when temperatures rise (Verberk et al., 2020). When warmer seasons for growth continue, pests which used to have just two generations each year can acquire a third period, leading to an overall explosion. A sudden decrease in the number of insects is more probable to occur in cooler regions and at higher elevations. While individuals are more effectively equipped to utilize the benefit of these shifts in the environment, certain insect varieties will reproduce quickly. Crowds of desert locusts have been associated with global warming (Ahmad, 2022). According to research, the leaves of soybeans become fewer in nutrients as the levels of CO₂ increase, meaning that plant-eating insects must consume greater quantities of food to meet their dietary requirements. Furthermore, in environments with high CO₂ levels, legumes become less equipped to protect themselves from insect predators (Fig. 1.1) (Hajam & Kumar, 2022). Jasmonic acids, an insect-killing chemical that the organism excretes if it detects a threat, are produced less frequently in response to CO₂. The insects can freely devour the foliage of soybean plants without this defense, which lowers crop production Table 1.1. This may not be an issue specific to soybeans, as the immune systems of a variety of plants decline under environments with elevated CO₂. In the past, pests, organisms, or fungi would die during the season's icy conditions (Velásquez et al., 2018). Seasons becoming drier or hotter promote fungus plant illnesses such as soybean rot and striped or brown/leaf rust to spread further north. The destructive plant infection known as soybean blight may wipe out entire crops in only a couple of weeks, causing growers to lose thousands of money in crop production (Batzer, 2022). A further instance involves the Himalayan Pines Insect beetle outbreak in British Columbia, Canada, that resulted in the death of thousands of pine trees due to the cold seasons becoming too warm to stop or prevent the insect's larva from developing. Many plant pests and diseases are additionally

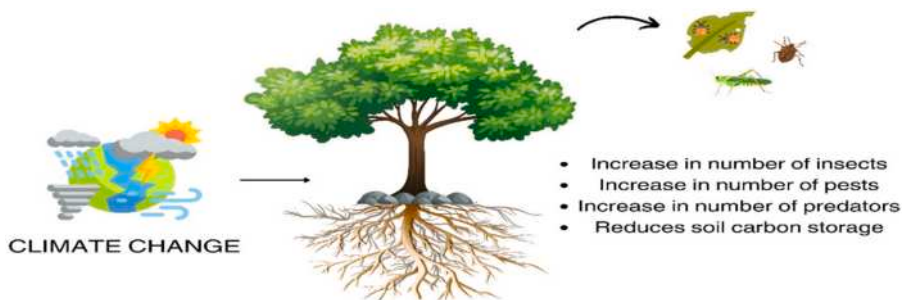


Figure 1.1 Tree along with climate change effects. Impact of climate change on plant ecosystem.

Table 1.1 Impact of climate change on insect pests in agriculture.

Climate change factor	Impact on insect pests	Examples
Temperature Increase	Accelerated lifecycle and population growth of pests. Expansion of pest ranges to new areas previously unsuitable. Increased overwinter survival of pests.	Faster reproduction rates, increased generations per season Spread of tropical pests to temperate regions (Bebber et al., 2014) Pests surviving milder winters, continuous infestation (Sappington & Rifai, 2018)
Precipitation Changes	Alteration in the distribution and abundance of host plants. Increased water stress weakening plant defenses against pests. Changes in breeding sites and habitat availability for pests.	Changes in crop suitability, increased food availability for pests (Fand et al., 2018) Weakened plant immunity, higher susceptibility to attacks (Bacete et al., 2018) Formation of new breeding grounds, expanded habitats (Sonenshine, 2018)
Extreme Weather Events	Disruption of pest population dynamics and behavior. Damage to natural enemies of pests affecting pest control. Increased post-event pest outbreaks due to weakened plants. Migration of pests to new areas following extreme weather events.	Temporary reduction in pest activity due to extreme events (Harvey et al., 2020) Reduction in populations of predator and parasitic species Pests capitalizing on weakened plants post-drought or flood (Prugh et al., 2018) Movement of pests after storms or floods to unaffected areas (Altieri et al., 2015)

being encouraged to spread by the rising frequency of inundation or severe rainfall (Yadav & Upadhyay, 2023).

1.4.2 Summer worms known as

One highly destructive agricultural pest called summer armyworm, *Spodoptera* are furipterid, was recently introduced to Sub-Saharan African nations. Global warming is responsible for increasing crop diseases and pests in the African continent, based on researchers (Khezzani, 2023). Because these highly destructive agriculture pests have a high potential for environmental adaptation, it is anticipated that their presence is going to spread to other parts of the world. The loss of crops from the autumn

armyworm, particularly grain, has a negative impact on yields in agriculture (Mupangwa, 2023).

1.4.3 Plant diseases, invasive plants, or herbicides

A framework for future studies on the effects of invasive organisms shifts in land use, and warming temperatures upon ecological systems (research facility in Fort Royal, which was Virginia, United States).

Similarly, to crops grown for food, weeds experience accelerated development phases and might benefit from CO₂ fertilization. Since most weeds were C3 plants, they will probably battle with greater intensity than they now do with C4 crops like maize (Vaccaro, 2023). But as the temperature rises, weedkillers might become more efficient. Precipitation is expected to increase due to climate change for certain locations, lengthening the period of heavy precipitation while increasing humidity in the atmosphere (Tamm, 2023). Such in addition to increasing temperatures, may encourage the growth of fungi-based illnesses. In a similar vein, greater stress with pests or disease vectors may result in greater levels of temperature and moisture (Hegde, 2023). Disease or recipient connections, especially the velocity of disease spread and plant resistance, are susceptible to change due to the climate. These illnesses have a bearing on the expenses of addressing and handling infected produce, in addition to the expenses of cultivating alternate crops that can yield fewer profits. According to studies, crop-damaging grow diseases' embryonic phases could shift primarily as a result to global warming. Diseases that affect plants spread as organisms move into locations having better environments mainly a result of changes in precipitation including temperatures brought about by global warming. This leads to agricultural damage from illness. Other monocrops that make up the vast majority of fields might be favored by environmental shifts above the varieties that are more ecologically varied plants. Plants have a benefit in shifting climates due to their molecular variety, and capacity in cross-breeding, so rapid development Table 1.2. These attributes enable them to adapt more quickly than many farmers' homogenous products offering us an ecological edge. Using herbicides effectiveness will fall with increasing carbon dioxide stages, that will improve plant resistance (Weller, 2019).

1.4.4 Innovative remedies for insect as well as weed problems

The difficulty of growing numbers of pests (pest management) has several potential remedies. The application of more insecticides in agriculture is a suggested answer. It comes with the advantage of becoming quite easy and reasonably economical, yet it might not work. Solvent tolerance is growing among numerous insects that are pests. Controlling biological agents is yet another suggestion for a remedy. This involves actions such as interspersing lines of native plants with rows of crops (Fig. 1.2. In terms of its total ecological effect, this option is advantageous (Choudhary et al., 2022). Additionally, due to the increased planting of natural plants, pest insects are currently developing resistance to insecticides. Nevertheless, more space is needed to plant many native species.

Table 1.2 Impact of climate change on crop production.

Climate change factor	Impact on crop production	Examples
Temperature Increase	Changes in phenology and growth stages of crops. Increased heat stress leading to reduced yields. Shifts in suitable areas for cultivation.	Early flowering, shorter growing seasons (Flohr et al., 2019) Reduced grain fills in cereals, fruit drop Expansion of tropical crops to higher latitudes (Wang et al., 2021)
Precipitation Changes	Increased pest and disease pressure. Changes in water availability affecting irrigation needs. Droughts leading to crop failures and decreased yields. Floods causing soil erosion, nutrient loss, and crop damage.	Spread of pests like locusts, new diseases (Zhang et al., 2017) Increased need for irrigation, water stress (Stenzel et al., 2019) Reduced yields in arid and semi-arid regions (Jabeen et al., 2022) Soil erosion, waterlogged crops, nutrient leaching (Kaur et al., 2020)
Extreme Weather Events	Altered patterns of rainfall affecting planting and harvesting. Changes in soil moisture impacting crop growth. Increased frequency of storms damaging crops and infrastructure. Hailstorms causing physical damage to crops. Extreme heatwaves leading to wilting and reduced yields. Early frosts damaging sensitive crops.	Delayed planting, harvesting disruptions Water stress, wilting, stunted growth (Blum, 2017) Crop lodging, physical damage to crops (Chauhan & Sharma, 2019) Damage to fruit crops, bruising in vegetables (Opara, 2014) Heat stress, reduced photosynthesis, yield loss (Akter et al., 2017) Frost damage to tender crops, bud loss (Yadav et al., 2015)

1.5 More indirect effects of the situation change

Insufficiency of nutrition pricing, as well as food insecurity. The effects of global warming on usage (keeping foodstuff from spoiling, becoming sufficiently nutritious to take in calories, etc.) as well as the fluctuation in food costs are impossible to estimate (Wani et al., 2023). A great deal of futuristic projection systems do show that market volatility is going to rise. Numerous people experienced a shortage of

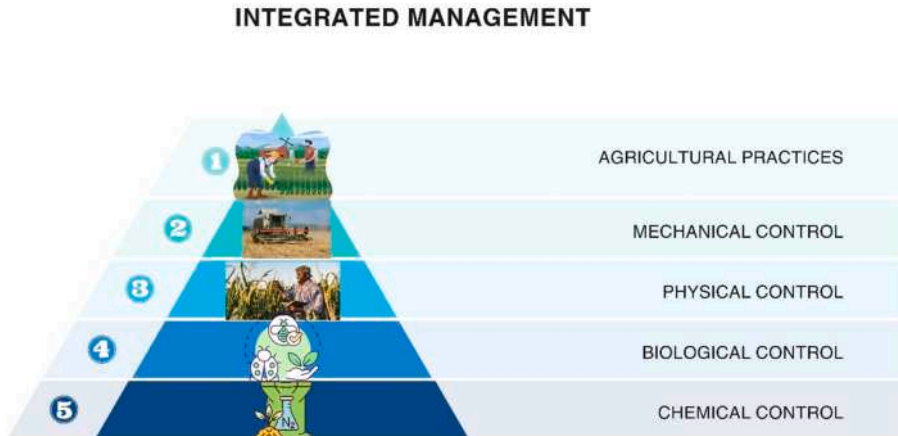


Figure 1.2 Different methods of management. Integrated management of insect pests.

food in 2020 as an outcome of global warming. Around 832,000 individuals were malnourished in the year 2020. The effects of global warming are significantly influenced by planned growth in society expansion, the economy. A research study published in 2020 discovered that the probability of being food insecure is currently increasing in several nations which currently experience hunger instability (Paquin & Falardeau, 2023). The implications with global warming upon malnutrition or deficiency of micronutrients are going to result in an absence at “decades of full wellness” in the years to come.

1.5.1 Increased expenses of food

Food insecurity is anticipated to result from the 80% increase in food costs predicted by the IPCC's Special Report on the Effects of Climate Change and Agriculture by 2050 as well (Beltran-Peña and D'Odorico, 2022). Poorer regions of the globe are going to be much more impacted by food shortages than affluent ones. Grain prices are expected to rise by 1%–30% in 2060 assuming an elevated emissions forecast (RCP6.0), which will have the greatest impact on low-income customers. That could raise the number of individuals in danger of going hungry by 1–185,000 more than would occur in a world without global warming (Holt-Giménez, 2019).

1.5.2 Increased expenses for producing food

Some landowners are not going to be able to pay for their produce due to rising expenses. Many nations with low incomes depend heavily on farming for employment, but rising expenses may necessitate job losses with wage reductions (Chetty, 2020). In response, other landowners are going to increase their produce costs, that is going to influence the reasonable price of agricultural products by being simply

transferred through consumers. Absent the food that is produced by certain landowners, families or communities would not have sufficient to consume. Rather than selling what they produce, these farmers decide to help them. As a consequence, agricultural output declines, and costs rise, with probable hunger in some areas of the globe (Assouto et al., 2020).

1.5.3 Fewer snow on the ground means there is greater farmland

Through decreasing the quantity of covered land, global warming may result in more agricultural land. According to 2006 research, the region's normal temperature was increased by a degree C during 1961 (far in excess of the other parts across the globe). Research on the consequences of climate change on Russian farming, yet, points to contrasting likely outcomes: Although researchers anticipate a growing amount of agricultural land toward north, also issue warnings about potential production losses including a greater possibility of dryness. There are likely more prospects in agriculture and forestry in the region known as the Arctic.

1.5.4 Because of mountains receding, there are fewer resources of water available for cultivation

Many regions rely largely upon glacial meltwater flow occurring around the warmer months of the year. As a result, if glaciers continue to advance as is now noticed, their melting ice is going to melt, which will decrease or completely stop flow. Reduced July flow of streams are going to render it harder to water crops and will make it harder to sustainably operate water bodies. The mountainous regions of Europe could lose between 28% and 44% of its ice mass under a 1.5°C climate change scenario, which will have an effect on those populations that rely on glacial and runoff waters for their way of life. The mountainous reservoirs support up to 60% of irrigated outdoors of the monsoon season with an extra 12% of agricultural output in the Indus River's basin. In the Himalayan rivers' catchment basin, there are about 2.5 billion individuals. More than 500 million individuals in India alone depend upon the Ganga River for their potable or agricultural water needs.

1.5.5 Fertility of the land with erosion

It is anticipated that the increased atmospheric temperatures seen in recent years will result in an increasingly active hydrologic cycle, involving greater rainfall episodes. The likelihood of drainage or harm to soil is increasing. Climate change could also have an impact on the fertility of soils. Human activities can cause more erosion in agricultural settings, including emissions of as much as 22% of the carbon in the soil over a 50-year period. Lands will become warmer due to global warming. It might then result in an estimated 35%–145% rise in the overall number of soil microbes. The variety for that bacterium of microbes might shift as a result of rising temperatures favoring the growth of certain types of bacteria. Increased carbon dioxide levels could speed up plant but soil microbial development costs, reducing

the earth's ecological cycle but benefiting oligotrophs, that develop less quickly as well as effectively use resources than copiotrophs.

1.5.6 Timely blooming' implications for seasons of growth

The record-breaking temperatures of the year 2019 caused a premature blossom while the public was prepared for purchase, throwing peony producers in Homer's Works Norway into a ride. Climate change has caused flowering seasons to rise, and the earliest flowers may endanger a plant's capacity to survive and reproduce (Lee, 2020). Regarding certain varieties of plants, premature flowering increases the likelihood of freeze harm and causes "mismatches" among crop blossoming as well as butterfly interactions. About 9% of farming output and close to 70% more commonly grown plant varieties depend on some part of pollination by insects, which is projected to be worth €153 million in the global economy every year. Additionally, since blooming requires excitement, as is typically provided by a protracted wintertime freeze, milder wintertime temperatures encourage the blooming of numerous flowers. Additionally, an organism is unable to reproduce when it does not blossom. However, if winter continues to be milder, plants might not experience sufficient frost to tell what's happening when April's temperature rises (Martin, 2020). The length of plant development periods is mostly influenced by weather. Increased temperatures would accelerate the process of growth. When growing a crop every year, the period for cultivation or reaping can be shorter (for instance, the time needed for gathering maize may be cut by as much as 4 weeks). Due to aging occurring more quickly, a shorter lifespan might have a negative impact on overall output. Agriculture phenomena modifications offer significant proof of how they react to current local global warming (Skendžić, 2021). This research and investigation of organic occurrences that take place regularly on a regular basis and the way they interact with climatic or changing seasons is known as phenomenology. During many areas within the North Hemisphere, phenomena both farming and timber production have advanced significantly.

1.6 Managing climate change: mitigation and adaptation

The main motivator for volunteer mitigation is the producers' assessment of the danger as well as the extent of global warming. But the capacity to adjust relies on how readily available the data is. Additionally, mitigation measures will lessen the number of individuals who are subject to environmental anxiety, however, individuals who remain susceptible to pressure will require ways to adapt. Producers can implement climate-resilient technologies by utilizing both conventional farming practices or agroecological systems of governance, such as biodiversification, managing soils, or collecting water. By assuring greater good wellness, of the soil, improved soil excellence, or decreased soil deterioration through various management methods, resistant grounds or farming applications are created, thereby

guaranteeing the availability of food amid global warming. The most effective approaches promoting education about climate change and the environment are those that concentrate upon regional, concrete, practical features that can be tracked by people's actions (Dwivedi, 2022). Most agricultural producers supported modifications, however, just a small minority supported GHG decreases demonstrating that it's important to concentrate on initiatives that combine mitigation and adaptation aspects. Technology for agriculture, socioeconomic or policy interventions, or conservation of resources technology may be used to categorize the primary adaptive approaches of mitigating. Because of a lack of information, farmers who are marginalized aren't as equipped to adapt to global warming, thereby raising their vulnerability to damage. Because of the monetary consequences or the absence of organizational measures, producers in African nations are also particularly susceptible to global warming. There are also many kinds of agricultural strategies, like changing planting times, that may be implemented to mitigate the effects of global warming. The best times to plant grain in Punjab, India, were determined as October 20–30 across the northeast, October 22–32 in the center, or October 24–34 across the southwest. While landowners in Africa south of the Sahara employ successive cropping methods or modify their planting times in accordance to climate with the plants' output damage, These are some straightforward methods for reducing greenhouse gas emissions, like paddy alternative drying out, around this time drainage, better diets for cattle, enhanced nitrogen use efficiency, or carbon in the soil (Hamidzadeh, 2023). Changes in when plants are planted or types are examples of straightforward adaptation efforts that could lessen the detrimental impacts of global warming. Spread of technology has a significant impact on how producers will react to global warming. Integration of markets, support of government studies, or strengthening capacity were the primary priorities. Since sustainable farming promotes minimal contamination trouble, the soil, variety in crops, or the upkeep of organic matter protection, it possesses the capacity to undo the deterioration brought upon gradually through traditional cultivation. Furthermore, sustainable farming results in greater land storage of carbon, decreased use of fertilizers, plus lower emissions of greenhouse gases. The fundamental tenets of conservation farming, which lay the groundwork for environmentally friendly farming methods, include minimal disturbance to the soil, rotation of crops, or ground covering (Bouwman et al., 2021). Producers overall southeast Asia have shifted to no plowing when growing wheat mostly due to the 15%–16% decrease in production costs. Furthermore, no-tillage farming increases both maize and wheat output while reducing variation. No-till techniques have been promoted as a substitute for traditional cultivation, to mitigate the effects of global warming by sequestering energy. However, the assertion is overstated because no-till farming produces relatively little extra carbon from organic matter.

The acceptance of protection farming or CA was impacted by a variety of variables, such as agriculturalist financial inspiration, the idea of private advantages, useful trading methods that provide the resources needed for CA application, the growth of farmer groups that promote regional adaptation, and the establishment of a suitable setting by partnerships between landowner groups as well as establishments

(Octavia, 2022) Improved farming techniques constitute key adaptation strategies, which are strongly affected through cultural regarding politics that consider meteorological unpredictability or severity as well as community, partisan, or financial factors (Fadaïro, 2023). Nutrient control is a crucial component since traditional industrialization of farming results in enormous financial damages, among whom Nutrients control accounts for over 80%.

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Flood risk and climate change: global and regional perspectives

2

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2.1 Introduction

2.1.1 *Climate change: a global challenge*

The change in world climate for the past several decades has largely been attributed to global warming. Issues related to climate change have been one of the major concerns among environmentalists, research organizations, and government agencies at local and international platforms considering its distinct and alarming consequences (Rajkhowa & Sarma, 2021). Climate change is a global challenge with its influence over various components of the ecological, environmental, socio-political, and socio-economic disciplines (Feliciano et al., 2022; Adger et al., 2005). Impacts of climate change range from rising sea levels, more variable and intense precipitation, more frequent flooding and droughts due to irregular weather patterns (Lipczynska-Kochany, 2018; Gasper et al., 2021; Michel et al., 2021; Murshed and Dao, 2020). Amongst various factors, anthropogenic activities are considered major drivers toward climate change (Murshed et al., 2022). Apart from the industrial revolution, other anthropogenic activities include excessive agricultural operations, which further involve the high use of fuel-based mechanization, burning of agricultural residues and fossil fuels, deforestation, national and domestic transportation sectors, etc. (Huang et al., 2016). Consequently, these anthropogenic activities lead to climatic disasters, damaging local and global infrastructure, human health, and total productivity (Abbass et al., 2022).

2.1.2 *Understanding impacts of climate change on the hydrological cycle*

Since water is the basic element of the life support system of Earth, it is of utmost importance to understand the impacts of climate change on water resources and their availability. The effects of climate change on water resource systems are usually expressed through the effects of hydrological variables on the hydrological cycle (Huntington, 2006). Many climate-change impacts on freshwater resources have already been observed, and further impacts have been projected, depending on region and season. The spatial and temporal distribution of river flows and groundwater recharge is affected by changes in temperature, evaporation, sea level, and, crucially, precipitation (Kundzewicz, 2008). The characteristics of the hydrological cycle and its associated extreme hydrological events, such as floods and droughts, are closely related to climate change, resulting in the loss of life and property (Gudmundsson et al., 2021; Pokhrel et al., 2021). The area and number of regions affected by both droughts and floods are growing (Conway & Schipper, 2011; Yang et al., 2019). The inundation of land due to flooding is a serious threat due to climate change. This chapter thus will discuss flood risks, one of the environmental issues, in connection with various factors associated with unusual weather conditions emerging from climate change and its impact on the environment. The significance of remote sensing datasets for flood monitoring will be discussed with relevant case studies in India and from a global context. Risk management initiatives and policies adopted and

implemented at the global and regional scale by various organizations to adapt and mitigate the adverse effects of flooding will also be addressed.

2.1.3 Flood induced damage: a global concern

One of the most threatening disasters impacting the world is flooding. Over the past decade, flooding has become a major problem in many parts of the world due to its social, economic, and environmental impact (Rehman et al., 2019). It has destroyed developmental infrastructure and increased human casualties around the globe (UNISDR, 2015). For example, 5 million people were displaced during the period 1960–2000 globally due to higher temperatures and heavy rainfall events. The number is expected to increase by 11.8 million people by the end of the 21st century (Marchiori et al., 2012). Four common types of floods include pluvial, fluvial, coastal, and flash floods (Ferguson et al., 2023).

2.2 Definition and scope of flood risks

A warmer climate induced by climate change can increase the risk of floods. Floods are generated differently in different geographic environments. For example, they may be generated by intense rainfall that exceed the infiltration capacity of the soil, or by rain falling on soil which is saturated. Floods may also be generated due to the melting of snow and glaciers. The effects of climate change on flood characteristics therefore vary across geographies, depending on the flood-generating mechanism (Arnell & Gosling, 2016).

2.2.1 Flood risks and impact on vulnerable populations

Flooding disproportionately affects vulnerable countries and communities around the world destroying buildings, and further worsening the economic status of vulnerable populations (Kikwasi & Mbuya, 2019). In Europe, over the past 150 years, the total number of urban areas that are vulnerable to flooding has increased by 1000% whereas in Sub-Saharan Africa, losses due to flooding are over US\$300 billion (Jongman, 2018). Flood-associated damage is a function not only of the depth, speed, and persistence of the floodwaters but also of the dissolved and suspended load that these waters carry including raw sewage and pollutants which often pose health hazards (Kundzewicz et al., 2013).

2.2.1.1 Impact on food security

Climate change-induced flooding is placing a stronger pressure on the resource farmers depend on, increasing the risks associated with disasters. The impacts of disasters are greater in the developing world (Marfai et al., 2008; Lolemtum et al., 2017; Pacetti et al., 2017) with these disasters have affected more than 1.9 billion people and caused over US\$494 billion in estimated damage between 2003 to 2013. The agriculture sector accounts for about 25% of the total damage and losses caused by climate-related disasters (Pratiwi et al., 2020).

The impact of flooding on agriculture and food security is a chief concern, particularly where flood events might be increasing (Nka et al., 2015; Fowler et al., 2007) or shifting in seasonality or character (i.e., flood type). This concern is evident in periodic reports issued by the Famine Early Warning System Network (FEWS NET), which is mandated with providing early warning of food crises to decision-makers (Reed et al., 2022). Emerging literature coupled with food security outlooks reveals several possible pathways through which flooding can impact food security. Many of these pathways lead to negative food security outcomes. For example, floods can lead to crop and livestock losses or damages, thereby either directly reducing the amount of food available to a household or indirectly impacting food security by reducing household income (Ahmad & Afzal, 2021; Akukwe et al., 2020; Pacetti et al., 2017). Floods may also damage infrastructure, such as roads, bridges, and storage facilities, which can prevent agricultural producers from accessing food markets to sell goods and purchase supplies (Codjoe & Owusu, 2011; Gustavsson, 2011; Ramakrishna, 2014). Saltwater intrusion from coastal flooding, such as from storm surges related to tropical cyclones, can prove damaging to crops in various ways, including marsh migration and groundwater contamination (Guimond & Michael, 2021). In addition, floodwaters can exacerbate public health-related challenges (Douglas et al., 2008; Rieckmann et al., 2018).

2.3 Factors contributing to unusual weather conditions which lead to flooding events

2.3.1 Increased precipitation and extreme rainfall events

As global temperatures rise, the atmosphere can hold more moisture, leading to more intense and frequent rainfall events. According to IPCC, for every degree Celsius of warming, the atmosphere holds approximately 7% more water vapor. This increased moisture content leads to heavier rainfall during storms, resulting in a greater likelihood of flash floods and river flooding events. For example, the devastating floods in Europe during the summer of 2021, which affected Germany, Belgium, and other neighboring countries, were exacerbated by record-breaking rainfall. Studies confirmed that climate change made this extreme rainfall event more likely, as the warmer atmosphere held more water, contributing to the intense rainfall (Kreienkamp et al., 2021).

2.3.2 Changing rainfall distribution patterns

Climate change is not only intensifying rainfall but also altering the rainfall distribution patterns. The shifts in rainfall distribution cause prolonged dry spells followed by intense downpours, which can overwhelm drainage systems and rivers, resulting in floods. The heavy monsoons in the countries of India, Nepal, and Bangladesh in 2017 caused widespread flooding leading to a loss of at least 1200 lives and displacing millions. This has been linked to shifting monsoon patterns

driven by rising temperatures and altered atmospheric circulation ([Sharma et al., 2018](#)).

2.3.3 Melting glaciers and ice sheets

Global warming is causing glaciers and polar ice caps to melt at an accelerated rate, contributing to rising sea levels. As glaciers melt, they add more water to river systems and oceans, increasing the risk of coastal and riverine flooding. The melting of glaciers can also lead to glacial lake outburst floods (GLOFs), which occur when the walls of a glacial lake fail and release large amounts of water downstream. The 2021 Chamoli disaster in India, where a glacier burst triggered massive floods in the Uttarakhand region, is an example of how climate change-induced glacial melt can lead to catastrophic flooding ([Zhao et al., 2022](#)).

2.3.4 Rising sea levels and coastal flooding

Rising sea levels, caused by both the thermal expansion of water and melting ice, are contributing to more frequent and severe coastal flooding. Coastal communities are particularly vulnerable as higher sea levels mean that even moderate storms can cause significant flooding. Moreover, higher sea levels increase the likelihood of storm surges, which can devastate coastal areas during hurricanes and typhoons. Cyclone Idai which struck Mozambique, Zimbabwe, and Malawi, in 2019 caused one of the deadliest floods in southern Africa's history. Rising sea levels in the region, driven by climate change, exacerbated the storm surge and flooding that devastated the coastal cities in these countries. Climate change was linked to the increased cyclone intensity and the resultant flooding more severe.

2.3.5 Urbanization and the heat island effect

In many regions, rapid urbanization combined with climate change is increasing flood risks. Urban areas often have poor drainage systems and large expanses of impervious surfaces, which prevent water from being absorbed into the ground. This exacerbates the effects of heavy rainfall, leading to flash flooding in urbanized cities. Climate change further worsens this problem by increasing the frequency of extreme rainfall events and intensifying the urban heat island effect, which can affect local weather patterns.

2.3.6 Atmospheric circulation changes

Climate change is altering large-scale atmospheric circulation patterns, such as the Jet Stream and the El Niño-Southern Oscillation (ENSO), which play crucial roles in determining weather conditions across continents. These changes can result in prolonged weather patterns, such as extended periods of rain or drought. In some cases, the slowing or stalling of weather systems can lead to persistent heavy rainfall over certain regions, causing devastating floods.

2.4 Increased flood vulnerability and risk

2.4.1 Flood vulnerable geographies of India

More than 80% of India's population lives in districts highly vulnerable to extreme hydro-met disasters. India is the seventh-most vulnerable country with respect to climate extremes ([Germanwatch, 2020](#)). An analysis by the Council on Energy, Environment and Water suggests that three out of four districts in India are extreme flood event hotspots, with 40% of the districts exhibiting a swapping trend, that is, traditionally flood-prone areas are witnessing more frequent and intense droughts and vice-versa ([Mohanty et al., 2020](#)). A study in 2021 measuring the climate change vulnerability of districts and cities in India revealed that the northern and north-eastern zones of India are more vulnerable to extreme flood events and their compounding impacts with the eastern and southern zones also becoming extremely prone to cyclones, floods, and droughts combined.

There are a multitude of reasons as to why floods occur with certain geographies being at an increased risk. Some of the reasons which increase the risk of floods in certain geographies of India are:

1. Rapid urbanization causes high runoff and less water detention and retention opportunities.
2. Unplanned urbanization along the flood plains or encroachments on water bodies or along the passage of natural drainage.
3. Shifting patterns of monsoon due to climate change and climate variability: Due to climate change, the melting of poles, an increase in sea levels with rising sea temperatures is observed which also causes more moisture to evaporate, resulting in heavier rainfall when clouds form. This is witnessed particularly in the monsoons leading to flash floods. Additionally, melting glaciers in the Himalayas contribute to more water in river systems, particularly during spring and summer.
4. Climate Variability caused by phenomena like El Niño and La Niña and Indian Ocean Dipole have been causing changing patterns such as higher rainfalls in usually dry areas which usually have inferior adaptive infrastructure to factor in for heavy flood runoffs. This leads to an increased risk of floods.
5. India has several large river systems, including the Ganges, Brahmaputra, and Indus, which are prone to flooding. These rivers carry huge volumes of water during the monsoon and can overflow their banks, especially in low-lying floodplains. The Brahmaputra and its tributaries are particularly known for causing severe floods in the northeastern part of India.
6. Many regions in India are located along the floodplains, particularly along the Ganges-Brahmaputra-Meghna basin, one of the most flood-prone areas in the world. These flat, low-lying areas are vulnerable to seasonal floods, which can inundate vast expanses of land. Large cities like Patna, Kolkata, and Guwahati are built on these floodplains, increasing the risk to lives and infrastructure.
7. The Himalayas contribute to flood risk through glacial melt and hence increased risk of GLOFs can occur, releasing huge volumes of water downstream, and causing flash floods.
8. India has a long coastline, extending over 7500 km. Coastal areas are prone to flooding due to storm surges, cyclones, and sea-level rise.
9. India's delta regions, such as the Sundarbans in West Bengal and the Mahanadi Delta in Odisha, are extremely flood-prone. These regions are located at the confluence of major

rivers and the sea, and experience frequent flooding due to high tides, storm surges, and riverine floods.

10. The Indo-Gangetic Plains with one of the highest population density, has the third highest ice deposit after the poles are followed by flat topography, which slows down the flow of water, leading to long-lasting floods.
11. Uttarakhand and Himachal Pradesh are mountainous regions with a complex landscape shaped by tectonic activity, steep gradients, and fragile geology, making them prone to landslides and floods, particularly during the monsoon season. However, these same geographical features also make the region a major source of hydropower and other economic activities like eco-tourism and horticulture. The challenge for both states lies in balancing economic development with the need to mitigate the growing risks posed by climate change, extreme weather events, and natural disasters like floods and landslides. Sustainable development, better planning, and disaster preparedness will be key to ensuring the long-term safety and prosperity of these regions.
12. Climate Change and Western Disturbances (WDs):

WDs are weather systems that originate in the Mediterranean region and travel towards the Indian subcontinent. These disturbances are essentially low-pressure systems that bring moisture-laden winds to the western and northern parts of India, especially during the winter months. WDs typically affect the Himalayan region, northwest India, and parts of the Indo-Gangetic plains, bringing rainfall and snowfall to these regions. These disturbances are crucial for the winter and pre-monsoon weather patterns in India, as they provide much-needed precipitation, especially for agricultural regions dependent on winter rains. The impact of WDs is mostly felt in the States of Punjab, Haryana, Uttarakhand, Himachal Pradesh, and Jammu & Kashmir.

 1. Shifting Jet streams, particularly the subtropical jet stream that guides WDs into India, have been observed to shift northward due to the warming of the atmosphere. This results in a change in the trajectory and frequency of WDs, causing more erratic precipitation patterns.
 2. Due to global climate warms, the atmosphere holds more moisture, which can increase the intensity of rainfall events during WDs.
 3. Warming in the Himalayan region has led to changes in snowfall patterns, with a reduction in snowfall and an increase in rainfall during WDs.
 4. Monsoon-WD Overlap: Traditionally, WDs primarily affect India during the winter months, while the monsoon dominates from June to September. However, climate variability has caused shifts in the monsoon onset and retreat, leading to a temporal overlap between WDs and the monsoon. This overlap increases the potential for joint extreme events, where intense rainfall from both systems occurs simultaneously.
 5. The convergence of moisture from the monsoon and WDs can result in intense localized rainfall events, leading to cloudbursts and flash floods. The 2021 Chamoli disaster in Uttarakhand was caused by a combination of intense rainfall and glacial activity, triggering flash floods.
 6. El Niño can also strengthen WDs, causing increased winter precipitation. Conversely, La Niña years usually bring stronger monsoons, but can also lead to more intense WDs in the northern regions, increasing the risk of floods.

Efforts toward climate change mitigation and adaptation in Indian cities, in the form of climate action plans, urban adaptation or resilience plans, or city resilience

strategies, have grown in scope over the past two decades. Additionally, sectoral plans have been created that address flood risks (such as flood mitigation plans), often guided by the National Disaster Management Agency to encourage localized, contextual hazard risk mitigation strategies for Indian cities. These are city-level efforts aligned with national and/or subnational climate goals and are framed within the broader field of climate policy and action. One of the initial steps in developing a climate action plan however would be in identifying the flood risks in the region through satellite imagery and datasets. The following section elaborates on how remote sensing datasets can help in timely flood monitoring for climate change adaptation and mitigation.

2.5 Remote sensing datasets in assessing flood events

Accurate and timely flood monitoring is crucial for effective disaster response and mitigation. Remote sensing has emerged as a critical tool in flood monitoring due to its ability to provide large-scale, real-time data across inaccessible or dangerous areas. Remote sensing datasets have immense potential in assessing flood events, flood monitoring, and assessments.

2.5.1 Real-time monitoring and early warning

Remote sensing technologies such as satellites, drones, and airborne sensors offer near-real-time data, enabling authorities to detect flood conditions early. This is particularly vital for issuing early warnings and mitigating flood impacts. Satellite-based systems like the synthetic aperture radar (SAR) can penetrate cloud cover, allowing monitoring even during heavy rainstorms. Moderate Resolution imaging spectroradiometer (MODIS), an optical sensor provided timely imagery and information during the 2010 Pakistan floods assisting in effective disaster response efforts.

Recent years have witnessed an increase in joint efforts of metrological departments of various countries through which various clusters of satellites take regular meteorological observations to understand the patterns of wind and cloud movements, the onset of monsoons and cloud temperature. These are used to understand where rainfalls will occur and the changing meteorological patterns due to climate change vulnerability. These observations play a vital role in flood forecasting and monitoring.

Recently a new kind of non-imaging remote sensing namely laser-based altimetry has evolved which can take very high precision ground-level observation from space. This helps in satellite-based water level and extent monitoring of rivers and dams.

2.5.2 Wide-area coverage and accessibility

Unlike traditional ground-based observation methods, which may be limited to specific locations, remote sensing offers extensive geographic coverage. Satellites like Landsat, Sentinel, and RADARSAT can cover entire river basins, coastal areas,

and floodplains, allowing monitoring of large areas at one stretch. This wide coverage is particularly useful for monitoring remote or inaccessible regions where ground-based systems may be impractical due to terrain, weather, or security concerns.

2.5.3 Mapping flood extent and dynamics

One of the most critical applications of remote sensing is mapping the spatial extent of floods. Using satellite imagery, authorities can delineate flood boundaries and estimate the area submerged by water. This information is valuable not only for response teams during the flood but also for post-disaster recovery and reconstruction efforts. Remote sensing also enables the tracking of flood dynamics, including the rate at which floodwaters spread or recede, helping to anticipate future impacts.

2.5.4 Assessing damage and post-flood analysis

Remote sensing allows for quick assessment of flood damage, especially in regions where on-the-ground surveys may be delayed. High-resolution imagery helps in assessing infrastructure damage, crop losses, and changes in land use. Additionally, by comparing pre- and post-flood imagery, analysts can evaluate the impact on ecosystems, urban areas, and critical infrastructure.

2.5.5 Hydrological modeling and risk assessment

Combining remote sensing data with hydrological models enhances flood prediction and risk assessment. Remote sensing provides accurate data on precipitation, soil moisture, and land surface properties, all of which are essential for simulating flood scenarios. These models help identify areas at high risk of flooding and guide long-term flood management strategies. For example, remote sensing data from the Global Precipitation Measurement (GPM) satellite was used to improve hydrological models, leading to better flood risk predictions for the Amazon Basin (Yoon et al., 2017).

2.5.6 Cost-effectiveness and efficiency

In addition, remote sensing reduces the cost and time required for large-scale flood monitoring compared to traditional methods. Satellite data can be accessed remotely and with the advent of open data initiatives [e.g., from NASA, the European Space Agency (ESA)], users can obtain critical data at no cost. This democratizes access to flood monitoring tools for resource-constrained regions that are often most vulnerable to flooding.

Decision makers all over the world in recent years have acknowledged the use of remote sensing in flood mitigation efforts with the agencies developing their own basin and subbasin scale hydrological and hydrodynamic models enforced with various meteorological forecasts. This helps in performing ensemble combined hydrological and hydrodynamic modeling for continuous observation of river discharge and water levels. With sufficient data getting available AI is also coming

into play for improved hydrological modeling in terms of accuracy, efficiency, and time requirement.

2.6 Case studies of flood events and the role of remote sensing

The following section captures some of the flooding events in recent history witnessed at the regional scale (India) and in the global scale and the potential and role of remote sensing in the assessment and monitoring of these events.

2.6.1 Regional

2.6.1.1 Mumbai, Maharashtra (2005)

Mumbai, India's financial capital, is a city highly prone to flooding, particularly during monsoons. Due to its geographic location along the Arabian Sea, coupled with intense rainfall, unplanned urbanization, and inadequate drainage infrastructure, the city faces recurring floods. Among the most severe floods in Mumbai's history was the 2005 flood when the city received 944 mm of rainfall in 24 hours. This extreme weather event led to widespread inundation of low-lying areas, and the shutdown of the city's transportation network, with over a thousand lives lost. Flooding in Mumbai is exacerbated by several factors: rapid urbanization, encroachment on natural drainage channels, the presence of informal settlements, and insufficient drainage systems that cannot cope with the volume of water during heavy rain events (Gupta & Nair, 2012).

One of the remote sensing data used during this event to assess the extent of flooding was SAR. SAR satellites such as Sentinel and RISAT can capture water surfaces, allowing for real-time flood monitoring even during heavy rainfall events (Sanyal & Lu, 2006). These remote sensing tools help authorities identify which areas are most severely affected and prioritize rescue and relief efforts accordingly.

While remote sensing provides the data, GIS plays a crucial role in analyzing and interpreting that data to assess flood damage. GIS integrates spatial data from various sources, including satellite images, DEMs, and hydrological data, to create detailed maps that show the spatial distribution of flood-affected areas. GIS was used post the Mumbai floods to map the flood extent and assess the damage to infrastructure, such as roads, railways, buildings, and utilities. This information helped authorities estimate the economic impact of the floods and plan for post-flood rehabilitation.

The integration of remote sensing and GIS has enabled more effective real-time flood monitoring and response as well. During the more recent Mumbai floods in 2017 real-time flood maps helped emergency response teams allocate resources more efficiently, directing efforts to areas that are most severely affected (Rangari et al., 2020).

Beyond emergency response, remote sensing and GIS are also invaluable tools for long-term flood risk assessment and mitigation. Flood hazard maps created using historical satellite data help city planners identify flood-prone areas and implement

strategies to reduce flood risk. For instance, GIS-based flood modeling can simulate different rainfall scenarios and their potential impact on the city, allowing for better urban planning and improved infrastructure design to withstand future flood events.

One notable example is the Brihanmumbai Storm Water Disposal System project, which aims to improve Mumbai's drainage infrastructure to mitigate flood risk. Remote sensing and GIS were used to model the city's drainage system and identify bottlenecks and flood-prone areas. This information helped engineers redesign drainage systems to handle higher volumes of rainfall, reducing the risk of future flooding (Sharma & Mote, 2017).

2.6.1.2 Chennai, Tamil Nadu (2015)

Chennai, the capital of Tamil Nadu, India, is another city which is highly vulnerable to floods. The city experienced one of its most devastating flood events in 2015 caused by unprecedented rainfall due to a combination of the monsoon, ENSO, and Indian Ocean dipole. The city recorded 1049 mm of rain in November, and a single day in December saw over 490 mm of rainfall, resulting in extreme waterlogging, the overflow of major reservoirs, and widespread inundation. The floods caused more than 500 fatalities, displaced over 1.8 million people, and inflicted economic losses of approximately \$3 billion.

During these floods, SAR data proved instrumental in monitoring floodwater dynamics while optical satellites such as Landsat and MODIS also provided valuable post-flood imagery. During and post the floods, remote sensing datasets were used to create flood hazard maps and hydrological models that simulate the city's drainage patterns under various rainfall scenarios. For example, digital elevation models (DEMs) generated using satellite data, such as from ASTER and SRTM, helped assess the topography of Chennai and identify low-lying areas prone to flooding (Ramachandra & Sreejith, 2016). These DEMs were combined with satellite-derived rainfall data from sensors like Tropical Rainfall Measuring Mission and GPM to model flood risks and understand how excessive rainfall could lead to waterlogging in certain neighborhoods.

Additionally, remote sensing datasets on land use and land cover (LULC) are crucial for assessing how urbanization has increased flood risks in Chennai. LULC maps created using Landsat and Sentinel-2 data revealed how the city's rapid expansion has encroached on natural drainage channels, wetlands, and lakes, which previously helped absorb excess rainfall. By overlaying flood risk maps with LULC data, authorities can identify vulnerable areas and take preventive measures such as restoring natural water bodies, improving drainage infrastructure, and regulating construction in flood-prone areas (Krishnamurthy et al., 2018).

Remote sensing has been used to identify areas of Chennai where natural drainage systems such as marshlands and lakes have been encroached upon. The restoration of these areas has been recommended as a flood mitigation strategy to reduce the severity of future floods. Satellite imagery continues to provide a valuable resource for monitoring these environmental changes and evaluating the success of flood prevention efforts.

2.6.1.3 Assam (2020)

Assam, a state in northeastern India is crisscrossed by rivers, most notably the Brahmaputra, which swells during the monsoon season and inundates large areas.

This River is highly prone to seasonal flooding and frequently overflows due to its wide and braided nature. The 2020 floods, one of the most severe in recent history, affected over 5 million people, claimed more than 100 lives, and submerged over 30 districts.

During the Assam floods, SAR data was used to track changes in the water levels of the Brahmaputra and its tributaries, providing detailed information on the extent of waterlogging in affected districts. In addition to SAR, optical satellites such as Landsat, Sentinel, and MODIS provide imagery that helps in identifying flooded areas, estimating crop loss, and assessing the damage to infrastructure. For instance, the Brahmaputra's floodplains and nearby villages can be mapped using Landsat data, which captures the extent of water spread during floods, helping in damage assessment and relief planning. Remote sensing datasets are also critical for predicting flood risks in Assam by providing historical flood data, monitoring precipitation, and mapping land use and topography. This data is used to develop flood risk maps, which help identify the region most vulnerable to future flooding.

Remote sensing datasets support not only real-time flood monitoring and damage assessment but also long-term flood risk management and mitigation strategies. A significant example is the monitoring of embankments along the Brahmaputra River. Remote sensing data has been used to map breaches in embankments, which are a common cause of flooding in Assam. Satellite imagery helps authorities identify vulnerable sections of embankments and plan their reinforcement before the monsoon season begins. In the future, integrating satellite data with on-ground sensor networks and hydrological models will allow for more accurate and timely predictions of potential embankment failures and floods.

The year 2024 saw Assam witnessing another episode of a spate of floods affecting 28 districts, especially in vulnerable areas like Dhubri, Darrang, and Lakhimpur. Rivers like the Brahmaputra, Subansiri, and Burhi Dihing breached danger levels, intensifying the flood's reach and causing further destruction to homes, roads, and critical infrastructure across more than 3000 villages. [Fig. 2.1](#) shows the pre and postflood levels from Sentinel-1 data.

Advancements in remote sensing technologies, such as the use of high-resolution SAR and the growing availability of free, open-access satellite data from platforms like Copernicus, offer new opportunities for improving flood management in Assam. The use of machine learning algorithms to analyze satellite data and predict flood risks is another promising development that can help reduce the impact of future floods.

2.6.1.4 Wayanad, Kerala (2019)

Kerala is one State in India which has been affected by floods nearly every year in the recent decade. Take the example of Wayanad, a district in Kerala which was severely affected by floods in 2018 and 2019 and was considered part of Kerala's worst flood

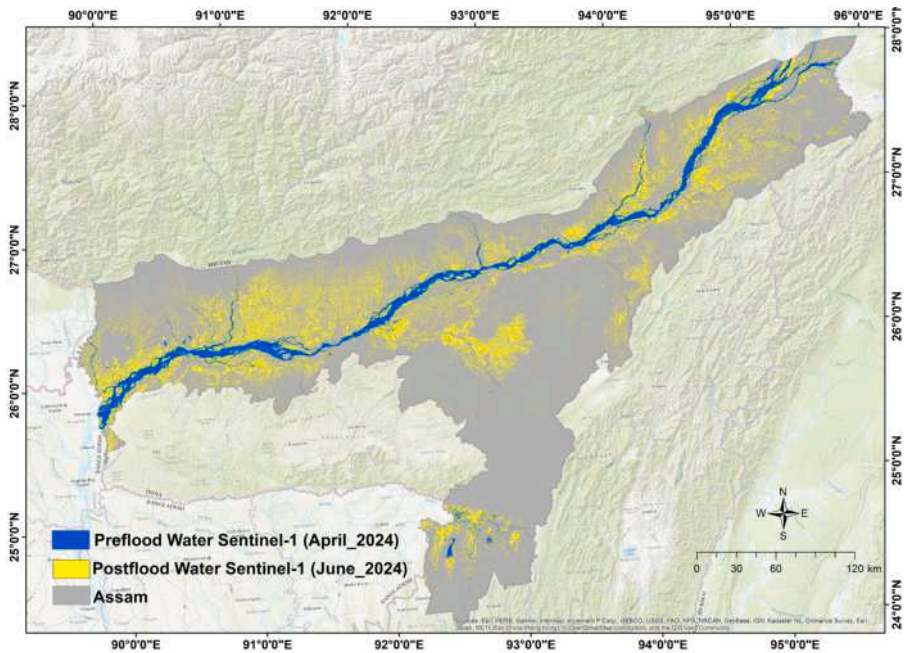


Figure 2.1 Pre and postflood Assam (2024). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

events in nearly a century. The floods were triggered by the southwest monsoon, which brought intense rainfall across the Western Ghats. In 2018, Wayanad received more than 500 mm of rainfall in just three days, which, combined with the steep terrain, caused landslides, river overflows, and widespread flooding. Over 15,000 people were displaced, and infrastructure such as roads, bridges, and homes were severely damaged. The agricultural sector also suffered massive losses, as crops were submerged under floodwaters. Landslides, another significant issue in Wayanad due to its hilly terrain, compounded the problem, further blocking rivers and causing more flooding. These flood events have called for the use of remote sensing and geospatial technologies for real-time flood monitoring, damage assessment, and long-term flood risk prediction.

In addition to remote sensing technologies in areas such as Wayanad which are also prone to landslides in view of its terrain, LULC data is another critical component for flood risk prediction. Remote sensing datasets from Landsat and Sentinel are used to monitor changes in land use, such as deforestation, urbanization, and agricultural expansion, which affect flood risk. The conversion of forested land to agricultural or urban use reduces the land's ability to absorb water, increasing runoff and flood risk. In Wayanad for example, LULC analysis has shown how deforestation on the slopes of the Western Ghats exacerbates the severity of landslides and flash

floods. Such analysis provides valuable insights for policymakers to implement better land-use planning and reforestation efforts aimed at reducing future flood risks.

2.6.1.5 Vijayawada, Andhra Pradesh (2024)

More recently, floods were witnessed in the city of Vijayawada, triggered by breaches in the Budameru rivulet and heavy rainfall leading to the displacement of thousands. Known locally as the “Sorrow of Vijayawada,” the Budameru once again overflowed, submerging neighborhoods and affecting nearly 644,536 people. Encroachments along its banks have worsened the flood's impact, with the affected low-lying areas suffering extensive damage. [Fig. 2.2](#) shows the extent of flood visualized through Sentinel-1.

Remote sensing played a pivotal role in managing these floods, providing essential data for real-time monitoring, mapping flood extent, and aiding in response efforts. Through satellite imagery and aerial surveillance, authorities could assess flood patterns and water levels accurately, informing quicker and more effective responses in the disaster-prone regions of Andhra Pradesh. Remote sensing data from satellites helped track rainfall intensity and the spread of water bodies, providing insights into which areas were at imminent risk of flooding and helping in issuing timely warnings and evacuations. This helped immensely in limiting the loss of lives.

2.6.2 Global

2.6.2.1 Africa (2020)

Countries in East Africa frequently experience floods often resulting from a combination of heavy seasonal rainfall, inadequate drainage systems, and overflowing rivers, including major river systems like the Nile, Tana, and Jubba. In recent years, floods in East Africa have been exacerbated by climate change, which has led to more intense and unpredictable rainfall patterns. The 2020 floods, which affected countries such as Kenya, Somalia, Uganda, and Ethiopia, over 1.5 million people and led to significant loss of life and economic damage. In countries like Somalia, where floods have occurred alongside conflict and food insecurity, the humanitarian impact has been severe.

During this flooding event in Somalia, where access to affected regions was difficult, SAR data helped identify flooded areas along the Shabelle and Jubba Rivers, guiding humanitarian organizations to focus relief efforts ([UNOSAT, 2020](#)) while in Kenya, remote sensing data from Sentinel was used to estimate crop loss in flood-affected regions, particularly in areas around Lake Victoria, where farmlands were submerged. This information is critical for post-disaster recovery and compensation for farmers.

Flood risk maps which can guide long-term planning and infrastructure development to reduce flood vulnerability have been developed for Ethiopia's Omo River Basin using DEMs to model the potential impact of heavy rains and predict which areas are most likely to be flooded. In addition, flood frequency maps generated from

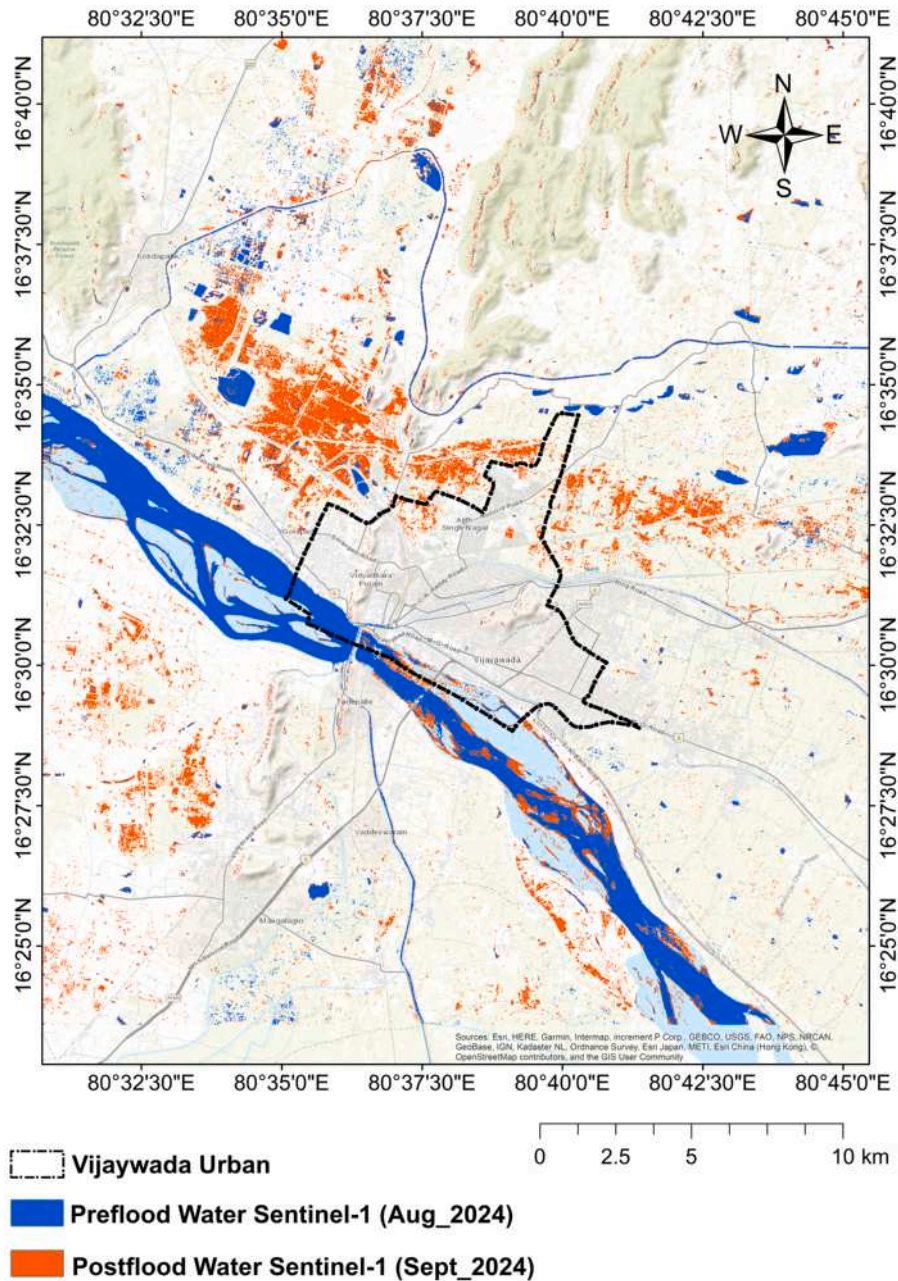


Figure 2.2 Pre and postflood extent during Vijayawada floods (2024). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

historical satellite data have been used in Uganda's Teso region to identify flood-prone areas and develop early warning systems.

2.6.2.2 Europe (2024)

The catastrophic floods that struck Europe in 2024, particularly in countries like Germany, Belgium, and parts of Southern Europe, highlighted the increasing threat of extreme weather events exacerbated by climate change. These floods caused widespread devastation, severely damaging infrastructure, homes, and agricultural lands. In response to this disaster, remote sensing technologies played a crucial role in both assessing flood damage and predicting future flood risks.

Satellite-based Earth Observation (EO) datasets, such as those from NOAA's VIIRS and the ESA's Copernicus satellites, allow for the monitoring of environmental variables like rainfall, soil moisture, and river levels, all of which are essential for flood forecasting. Tools such as the Global Flood Awareness System (GloFAS) combine EO data with hydrological models to provide early warning systems for flood events.

Recent studies indicate that Europe is the world's fastest-warming continent and floods caused by Storm Boris in Central Europe (and made worse by climate change) paint a gray picture. However, the storm was well predicted using satellite-based dataset add tools which helped in reducing the loss of lives and limiting infrastructure damage.

Despite the success of remote sensing in flood management, there are limitations. Persistent cloud cover, common during floods, can reduce the effectiveness of optical sensors. However, SAR overcomes this obstacle, though it faces challenges in urban areas and dense vegetation. Future improvements in flood monitoring systems may include the integration of SAR data with ground-based observations and advanced machine learning algorithms to enhance the accuracy of flood predictions and assessments.

2.7 Frameworks for flood mitigation strategies

While satellite imagery and associated datasets play a critical role in flood monitoring, and forecasting as climate adaptation strategies it also highlights a need for frameworks and policies at the national and international level for flood adaptation and mitigation. For example, the Government of India has notified the National Geospatial Policy (2022). Through this policy, the Government aims to develop a framework that will enhance the efficiency of implementing data in everyday lives. This legal framework is envisioned to support the liberalization of Geospatial sector while democratizing data by 2025 ([Awana, 2023](#)). Democratization of data in this sector can help in reducing flood risks and hazards as well as play a role in flood adaptation and mitigation in combination with on-ground interventions. Flood mitigation approaches fall into two categories—structural and nonstructural. Structural forms of mitigation mitigate harm by reconstructing landscapes while nonstructural measures reduce damage by removing people and property out of risk

areas. This calls for a need to first understand the fundamental concepts of hazard, vulnerability, and risk in the context of urban flood management. Flood risks are defined as a product of hazards, exposure, and vulnerability (Ferguson et al., 2023).

2.7.1 Hazard, vulnerability, and risk in urban flood management

2.7.1.1 Hazard

In the realm of urban flood management, a hazard refers to the potential occurrence of an event that can cause significant damage. These hazards are typically related to excessive rainfall and flooding. Climate change exacerbates these hazards, leading to more frequent and intense storms. Urbanization, with its expansion of impervious surfaces, further intensifies runoff and flood risks. Inadequate drainage systems compound these problems, resulting in severe flooding during storm events. Understanding the types and sources of hazards is crucial for effective flood management planning (Fig. 2.3).

2.7.1.2 Vulnerability

Vulnerability is the degree to which a system, community, or individual is susceptible to the adverse effects of hazards. Factors such as population density, socio-economic status, infrastructure condition, and emergency service capacity influence vulnerability. In urban areas, high population density and inadequate infrastructure increase vulnerability to stormwater hazards. Vulnerability assessments help identify the most at-risk areas and populations, guiding targeted interventions to reduce potential impacts and enhance resilience.

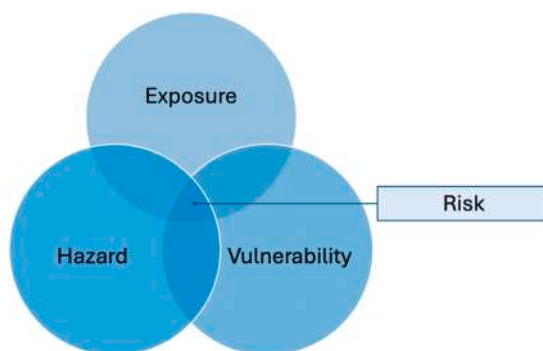


Figure 2.3 Flood risks as a product of hazards, vulnerability and exposure.

Source: Adapted From Ferguson, Scott, Van Ledden, Mathijs, Rubinyi, Steven, Campos, Ana & Doeffinger, Tess. (2023). *Urban flood risk handbook: Assessing risk and identifying interventions*. Washington, DC: World Bank. <https://doi.org/10.1596/40141>.

2.7.1.3 Risk

Risk in urban flood management is the combination of the probability of a hazard occurring and the magnitude of its potential impacts. It is a function of both hazard and vulnerability. Risk assessments involve analyzing the likelihood of flooding events and their potential consequences on people, property, and the environment. Effective risk assessment helps prioritize areas for intervention and allocate resources efficiently, ensuring that the most vulnerable and high-risk areas receive the attention they need.

2.7.2 Planning and strategy development

To aid in the analysis and planning of urban flood management, a comprehensive framework is necessary. [Table 2.1](#) outlines specific criteria and data layers essential for understanding hazards, vulnerabilities, and risks associated with flood management.

The table serves as a vital tool for flood management. It provides a structured approach to analyzing hazards, vulnerabilities, and risks, guiding the development of effective mitigation strategies and the implementation of resilient infrastructure. By integrating this information, administrators can make informed decisions to protect urban areas from the adverse impacts of flooding events.

2.7.2.1 Application for Administrative Decision-Making and Implementation

[Table 2.1](#) provides a framework for flood management which can be used by planners and decision-makers in the following ways:

1. Planning

Planners can use the table to identify high-risk areas and prioritize them for detailed analysis and intervention. By understanding the interplay between hazards and vulnerabilities, planners can develop targeted strategies to mitigate risks effectively.

2. Strategy Development

Administrators can formulate risk mitigation strategies using the data provided in the table. These strategies may include improving drainage systems, implementing flood defense structures, and enhancing community preparedness through education and awareness campaigns.

3. Infrastructure Needs

The table helps identify infrastructure gaps and needs. For example, areas with high runoff and inadequate drainage can be targeted for drainage network expansion or green infrastructure projects like rain gardens and permeable pavements.

4. Environmental Impact Assessment

Incorporating data layers for environmental impact assessment ensures that flood management strategies not only manage floods effectively but also promote environmental sustainability. This holistic approach helps balance urban development with the preservation of natural ecosystems.

Table 2.1 Criteria and data layers essential for understanding hazards, vulnerabilities, and risks associated with flood management.

Criteria	Data layers	Hazard analysis	Vulnerability analysis	Risk analysis	Risk mitigation strategy	Infrastructure Needs	Environmental Impact
Urbanization	Percentage of urban area, Total urban area, Urban sprawl data	Mapping urban areas prone to flooding due to high runoff	Identifying areas with high population density and inadequate infrastructure	Assessing the impact of urban sprawl on flood risks	Strategies to manage urban expansion and enhance drainage systems	Expanding drainage networks, Implementing green infrastructure	Minimizing urban sprawl's impact on natural water absorption
Land Cover Changes	Loss of green cover (deforestation, vegetation loss), Loss of blue cover (wetlands, water bodies)	Identifying areas where vegetation loss increases flood risks	Assessing the vulnerability of areas losing natural flood buffers	Evaluating how land cover changes influence flood hazards	Reforestation, Wetland restoration	Creating green spaces, Restoring wetlands	Enhancing natural flood mitigation capabilities through land cover restoration
Topography	Maximum and minimum elevation, Slope analysis, Curvature	Identifying flood-prone areas based on topography	Assessing the susceptibility of low-lying areas and steep slopes to flooding	Analyzing the impact of topography on flood dynamics	Implementing flood defenses in high-risk topographical areas	Constructing levees, Elevating buildings	Ensuring topographical interventions do not disrupt natural water flow patterns

(Continued)

Table 2.1 (Continued)

Criteria	Data layers	Hazard analysis	Vulnerability analysis	Risk analysis	Risk mitigation strategy	Infrastructure Needs	Environmental Impact
Hydrology	Watershed boundaries and area, Stream network/drainage, Drainage order, Curve Number (CN) for different land uses, Flow accumulation, Height Above Nearest Drainage (HAND Index), Stream power index, Topographic position index, Topographic wetness index, Sediment transport index, Topographic ruggedness index, Historical flood events, Pluvial and fluvial flood (area)	Mapping flood-prone watersheds and drainage networks	Identifying vulnerable watersheds and drainage systems, Assessing historical flood data and trends	Evaluating the likelihood and impact of floods based on hydrological data	Developing watershed management plans, Enhancing drainage capacity	Expanding drainage infrastructure, Creating retention basins	Balancing hydrological management with environmental sustainability, Minimizing impact on aquatic ecosystems

5. Risk Mitigation Strategy

By combining data on hazards, vulnerabilities, and risks, decision-makers can develop comprehensive risk mitigation strategies. These strategies may include structural measures like building levees and nonstructural measures like land-use planning and public awareness campaigns.

6. Implementation

The data layers provide a basis for the practical implementation of flood management plans. They guide the design and construction of stormwater infrastructure, ensuring that interventions are both effective and sustainable.

2.8 Conclusion

Climate change is significantly altering weather patterns, and its effects are increasingly evident in the rising frequency and severity of floods. From heavier and more intense rainfall to melting glaciers and rising sea levels, climate change is contributing to a variety of flood risks worldwide. These changing patterns pose serious challenges for communities, governments, and disaster management agencies as they work to adapt to a world with more extreme and unpredictable floods. Understanding the link between climate change and flooding is critical for developing strategies to mitigate the impact of these disasters in the future.

Satellite imagery and associated datasets have played an important role in flood monitoring as well as forecasting helping in adaptation strategies. It has helped in identifying high-risk zones and informing policymakers and urban planners to take preventive measures, such as improving drainage systems, constructing flood defenses, and regulating land use in flood-prone areas. As remote sensing technologies continue to advance, they will play an even more prominent role in mitigating the impacts of flooding and ensuring more resilient communities worldwide. By understanding the key concepts of hazard, vulnerability, and risk, and utilizing comprehensive planning tools, cities can enhance their resilience to floodwater challenges and create safer, more sustainable urban environments.

Techniques like remote sensing, hydrological modeling, hydrodynamic modeling, and improved weather predictions, improving the ground monitoring networks with the understanding of hazards, risks, and vulnerability of the settlements can help in evidence-based decision making by the administrative decision-makers by supporting the following:

1. Help develop a high-resolution Flood Risk Atlas to map critical vulnerabilities at the district level and better identify, assess, and project chronic and acute risks such as extreme flooding events. A Risk atlas can also support monitoring and forecasting, which are indispensable given the rapid intensification of floods and other extreme events.
2. Development of integrated multiscenario high-resolution hydrological and hydrodynamic models to convert weather predictions into actual flood indentations maps.
3. Help undertake flood-sensitivity-led landscape restoration (based on datasets) focused on rehabilitating, restoring, and reintegrating natural ecosystems as part of the developmental process.
4. Help integrate flood risk profiling with infrastructure planning to increase adaptive capacity.
5. Improving urban stormwater management systems taking a border basin sake approach for seeing stormwater as a resource rather than hindrance.

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Impact of xenobiotics under a changing climate scenario

3

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3.1 Introduction

In the era of urbanization and industrial growth, the contamination of the environment by various xenobiotics has become a major threat to the whole human civilization (Malla et al., 2018; Mishra & Srinivasan, 2001). According to Schlegel (1986), xenobiotics are chemical substances that are not naturally formed in organisms, but their trace amount is present in the organisms. Xenobiotic is the combination of two Greek words, where *xeno* means unnatural or foreign substance and *biotic* means life. Xenobiotics can be of both inorganic and organic forms and may imitate the action of biological compounds that are crucial for life (Essumang, 2013). The generation of both organic and inorganic xenobiotic substances from the industrial processes causes widespread pollution of the environment. The anthropogenic sources of these toxic xenobiotics include discharge from industries,

medicinal drugs, agricultural field wash-off, household wastes and transportation (Essumang, 2013). Industrial wastes such as dyes, solvents, pharmaceuticals, hydraulics, pigments, halogenated compounds, etc., and wash-off from agricultural fields due to excess use of fertilizers, herbicides, and pesticides contribute significantly to the rise of xenobiotics in the water bodies. In addition, medical wastes have been well known for their prolonged persistence in the environment and slow or no biodegradation in the ecosystem. Xenobiotic compounds can be classified as environmental pollutants, food additives, pesticides, and carcinogenic substances. Once discharged into the environment, xenobiotic substances enter into the food chain, causing a harmful impact on each trophic level and adversely affecting the health of animals and humans due to their bioaccumulating effects (Dhakal et al., 2018; Embrandiri et al., 2016; Godheja et al., 2016). The story of xenobiotic contamination dates as early as the 1960s, when the discovery of methyl mercury and dichloro-diphenyl-trichloroethane (DDT) residues in marine life sparked public awareness about the accumulation of these toxic chemicals in the ecosystem (Ashauer et al., 2012; Baun et al., 2012; Derby et al., 2021; Maurya & Malik, 2016; Zhou et al., 2022). On further investigation, it has been found that these substances have carcinogenic, teratogenic, and mutagenic effects on all organisms. Removal of xenobiotic compounds is necessary. Various chemical and physical methods such as adsorption, filtration, chemical precipitation, electrolysis, coagulation, and ozonation have been used to degrade these compounds. However, these methods are not cost-effective and require large space for the conduction of complicated processes.

3.2 Types of xenobiotics

Xenobiotics can be either endogenous or exogenous.

3.2.1 Endogenous xenobiotics

Endogenous xenobiotics are toxic chemical compounds such as bilirubin, bile salt, steroids, certain fatty acids, and eicosanoids that are biologically synthesized in human bodies as a by-product of various metabolic processes. In addition to these compounds, some organisms may also produce various toxic substances as a part of their defense mechanisms such as bacterial toxins, cytotoxins, and herbal toxins.

3.2.2 Exogenous xenobiotics

Toxic compounds that are not naturally produced by an organism but enter in the body via various sources such as foodstuffs, medicines or are inhaled from the environment are considered as exogenous xenobiotics. Most commonly present exogenous xenobiotics in the environment include pollutants from the factories, fertilizers from agricultural fields, food additives, and household wastes.

3.3 Chemical nature of the xenobiotics

Xenobiotic compounds are high molecular weight complex molecules that are joined by non-physiological bonds and partially or insoluble in water. These compounds have some structural similarities to the natural compounds from which they originated. These complex molecules can be halogen-substituted aliphatic compounds, polycyclic aromatic hydrocarbons, aromatic hydrocarbons, organic and nitroaromatic compounds, aromatic amines, synthetic polymers, and azo compounds (Southorn & Garth, 1988; Spain, 1995).

3.4 Impact of xenobiotics on environment

The release of toxic compounds in the environment due to anthropogenic activities such as urbanization and uncontrolled population expansion is a cause for global concern. The enormous amount of toxic chemicals released into the environment during the Industrial Revolution resulted in widespread ecosystem contamination (Embrandiri et al., 2016). During the Industrial Revolution, scientific and technological advancement led to the over-exploitation of natural resources, which destroyed the ecological balance of various ecosystems (Sikandar et al., 2013). The uncontrolled use of veterinary and human drugs and pharmaceutical wastes produced is another well-known contributor to environmental pollution. As compared to other xenobiotics, the impact of medical waste on surrounding flora and fauna is more prominent.

3.4.1 Negative impact of xenobiotics on water-bodies

From ancient times, major human establishments have taken place near water bodies due to the presence of a continuous supply of water required for various activities. However, with time, various anthropogenic activities such as urban industrialization, building construction, transportation, and housing wastes pollute the surface and underground water systems. Several trace elements and xenobiotic substances such as synthetic organic chemicals, pesticides, phthalates, and polycyclic aromatic hydrocarbons are found in various water bodies (Mishra et al., 2019). Xenobiotic substances can reach water-bodies through various sources such as surface water running from agricultural fields and streets, airborne particulate deposition, solid waste burning, and untreated release of wastes from commercial factories, sewage effluents, and fossil fuel burning (Essumang, 2010). Xenobiotic substances also reach the water table through leaching processes that contaminate the potable water source and affect the integrity of the aquatic ecosystem (Fent et al., 2006). The presence of xenobiotics above the threshold value induces oxidative stress in aquatic organisms. In a recent study, Ibor et al. (2019) showed a significant rise in the level of oxidative stress in the fish fauna of Eleyele Lake, Nigeria. Similarly, (Burgos-Aceves et al., 2018) showed that xenobiotic compounds negatively regulate the homeostasis condition in fish, leading to higher oxidative stress due to the higher formation of reactive oxygen species in cells along with lower functioning of antioxidative system.

3.4.2 Impact of xenobiotics on soil

Xenobiotics such as DDT, dioxins, chlordane, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and nitroaromatic substances are major threats to soil ecosystem. Along with these pollutants, other xenobiotic substances like nitrobenzene, benzene, xylene, ethylbenzene, toluene, aniline, and chlorinated solvents could also disturb the soil ecosystem (Salem et al., 2017). Anthropogenic activities stimulating the level of these toxic compounds include fuel combustion, military movement, industrial activities, use of pesticides, insecticides, and fertilizers, and soil modification for higher yield of crops (Alkorta & Garbisu, 2001; Samanta et al., 2002). Chemical characteristics of xenobiotics and site conditions influence their bioavailability, and distribution in soil, with soil organic matter playing an important role (Borpatragohain et al., 2019). Over the last century, pesticides such as insecticides, herbicides, fungicides, bactericides, algacides, etc. that have been widely used in the agricultural field significantly deteriorated the soil ecosystem and also negatively affected the surrounding flora and fauna (Schwitzguébel et al., 2006). Various environmental factors such as temperature, soil pH, and moisture content significantly impact the behavior of xenobiotics in the soil. Various methods have been applied in the past to minimize the concentration and effects of these xenobiotic compounds in the soil ecosystem. One possible strategy is binding xenobiotic compounds to soil organic matter. Many xenobiotics and their degraded products resemble humic precursors and are frequently used in humification (Hayat et al., 2010).

3.4.3 Impact of xenobiotics in air

Human being generally releases a huge amount of toxic pollutants into the environment every day. Some xenobiotic compounds such as polycyclic aromatic hydrocarbons are exclusive organic environmental pollutants released due to incomplete burning of materials and gas particles. There are various sources of xenobiotics in the air such as the burning of fossil fuels, grilling of food and sometimes burning of agricultural waste as well. In addition, smoke released from transport vehicles and industrial emissions also contribute to the release of polycyclic aromatic hydrocarbons into the environment (Essumang et al., 2006). These xenobiotic compounds reach different tropic levels and disturb the food chain. These compounds may affect the climate and environment and some xenobiotics are carcinogens which may cause a number of problems in human beings.

3.4.4 Impact of xenobiotics on plants

Xenobiotics present in air, soil, and water severely affect the physiology and morphology of plants. According to (Verma & Singh, 2006), particulate matter released from automobile industries changes the protein structure, photosynthetic pigment, cysteine content, foliar surface, and leaf area of plants. Along with this, a diverse range of xenobiotics with various structures also hampers the signal transduction and gene regulation in plant cells. Xenobiotics which are phytohormone

analogs, significantly affect the function and signaling of intrinsic hormones (Ramel et al., 2012). Metals such as zinc, iron, and copper are required for normal growth of plants but show deleterious effects on being accumulated in cells above the threshold level. In addition to these metals, lead, cadmium, arsenic, and mercury also show deleterious effects in plant cells even at lower concentrations (Kumar & Aery, 2016). According to (Pande et al., 2022), xenobiotics induce the formation of reactive oxygen species in plant cells that lead to DNA damage and also inhibit the function of various signaling receptors such as tyrosine kinase receptors and G-protein coupled receptors.

3.4.5 Impact of xenobiotics on mammals

Xenobiotic exposure in animals is one of the major problems for the scientific community. Xenobiotic exposure in animals might occur through the application of pharmacologic drugs or ingestion of contaminated foods that are earlier exposed to xenobiotic compounds. The chemical and structural property of these xenobiotic compounds plays a vital role in determining the amount of damage caused in exposed organisms (Perkins & Hankenson, 2020). According to (Kobzev et al., 2020), higher release of xenobiotics in the environment has increased the rate of mortality, causing higher allergic reactions, failure of the immune system, metabolic disorders, and genetic alteration in animals. Humans are constantly exposed to a diverse range of xenobiotics via medication and other processes such as ingestion, breathing, dermal contactor or any other intravenous routes (Korrapati & Mehendale, 2005). Xenobiotics may alter the human gut microbiome leading to dysbiosis, which is indirectly linked to various undesirable health outcomes. The detoxification system of the human body constantly tries to reduce the level of xenobiotics in the body; however, at higher concentrations, these systems also fail to perform their normal function. On being disturbed, bioaccumulation of toxic compounds occurs in the body that leads to chronic disease and DNA damage. The toxicity of xenobiotics depends on the tolerance capability of organisms. A wide range of xenobiotics are quite harmful and have irritating effects on various human organs and systems directly or indirectly (Kucherenko et al., 2021). Along with humans, the toxic effect of xenobiotic compounds is also quite prominent in animals. Earlier (Macdonald & Gledhill, 2007) showed that ingestion of ivermectin, a popular acaricide and anthelmintic is harmful for some breeds of dog and mouse strains due to lack of p-glycoprotein. Similarly, (Khan & Rampal, 2014) also showed that pazufloxacin and meloxicam cause oxidative damage in rabbit cells along with higher lipid peroxidation and lower glutathione content.

3.4.6 Impact of xenobiotics on marine life

Xenobiotic compounds have a negative impact on marine life by inhibiting various metabolic processes mostly in developing fish embryos, leading to functional and morphological abnormalities which might also lead to their death. Arya and Haq (2019) reported altered body shape and abnormalities in the body along with hatching delay and larval death in fishes being exposed to higher concentration of xenobiotic

compounds. For marine life, dyes and paints are major forms of xenobiotic compounds because they inhibit gas exchange and also restrict the penetration of sunlight in the water bodies (Abdelkader et al., 2011). In addition, wash-off from agricultural fields containing pesticides, herbicides, insecticides, and other chemicals such as carbamates, organophosphorus, nitrophenols, and synthetic pyrethroids are also major sources of xenobiotic pollution in water bodies.

3.5 Xenobiotics and climate change

Along with eutrophication and climate change, the unregulated release of xenobiotics in the environment is one of the major causes of concern to the ever-growing human population. However, very few studies have been conducted in the past to show the direct relation between climate change and the release of xenobiotics in the environment. The release of xenobiotics in the environment is going to significantly rise in the coming future; thus, it will be interesting to investigate the effect of xenobiotics on climate change (Bloomfield et al., 2006).

The impact of xenobiotic compounds on the environment depends on various factors such as vapor pressure, and water solubility of the compounds along with environmental factors like temperature, humidity, nature of the compound, and its concentration. Coscollà et al. (2011) reported that erosion of soil particles by wind, volatilization process from soil and plants, and emission of pollutants from the air also impact climate change. In addition, Gagne et al. (2007) reported that higher temperature increases the activity of microorganisms that further stimulate the uptake of xenobiotic compounds. Various studies have reported that environmental factors change the nature of xenobiotics that variably affect climate change at different places (Ma et al., 2004; Meyer & Wania, 2008; Sweetman et al., 2005). According to (Sinkkonen & Paasivirta, 2000), higher temperature of soil and water induces the degradation of xenobiotics in the environment that further enhances the concentration of toxic by-products in the ecosystem. Beyer et al. (2003) reported higher volatilization of xenobiotics in water and soil due to higher temperature and photo-degradation. Along with abiotic factors, several biotic factors also regulate the behavior of xenobiotics in soil and may impact the migration of species of compounds. Some distributional processes of climate change will change the frequency and number of xenobiotic compounds which are used in agriculture and they thereby can change the climate (Chen & Mccarl, 2001; Reilly et al., 2003). In past, Van Den Berg et al. (1999) reported that volatilization is an important factor that led to higher global warming which eventually enhances the volatilization of xenobiotic compounds in soil and water.

3.6 Biodegradation of xenobiotic compounds

Various species of microbes can degrade xenobiotic compounds depending on their types. In addition, xenobiotic compounds especially pharmaceutical compounds are accumulated within organisms undergoing biochemical modification via specialized

enzymatic systems. Enzymes such as cytochrome P450 are secreted in liver which helps in the degradation of xenobiotic compounds that are eventually eliminated from the body via different excretory processes. According to (Bonjoko, 2014), each stage in the degradation of xenobiotic compounds is catalyzed by specific enzymes secreted in the degrading cells. The major by-products formed due to the degradation of xenobiotic compounds in the body are carbon dioxide and water.

3.7 Conclusion

With the continuous rise in population and urbanization, there is a continuous risk of xenobiotic contamination in the environment. Right from our daily care products to agricultural uses, the existence of harmful xenobiotics has been detected. Currently, various researchers have focused on the impact of xenobiotic contamination on climate change. Xenobiotic pollution indirectly affects climate change by increasing the temperature of the ecosystem. In addition, xenobiotic contaminants may get admixed with ground and surface water bodies, thereby affecting the flora and fauna of the surrounding ecosystem. Additionally, xenobiotic compounds accumulate in the lower organisms of the food chain which eventually affects the whole food web at each trophic level as well as the nutrient cycle.

To minimize the additive effect of climate change and xenobiotic pollution on the environment and human health, awareness among the population needs to be enhanced about the ecosystem and the use of xenobiotic compounds. Increasing temperature which is indirectly linked with xenobiotic pollution significantly affects the nature and composition of soil which ultimately lowers the crop yield, leading to food scarcity for the growing population. Currently, there are a huge number of researches focused on determining ways to minimize the effect of xenobiotics on climate change and ecosystems as well as on making sustainable use of these xenobiotics for sustainable living with the environment.

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Impact of climate change on plant–microbe interactions under agroecosystems

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4.1 Introduction

Currently, the current situation due to climate change has produced the need to create agricultural systems in a sustainable and ecological way. Agriculture is one of the main economic activities in the world and is responsible for 19–29% of the total greenhouse gas (GHG) emissions in the world (World Bank, 2023). This figure is expected to increase by 7.5% in the next ten years (Oecd-Fao, 2023), which demonstrates the importance of promoting more sustainable agri-food systems.

The main GHG produced by agriculture is methane (CH₄), the gas responsible for more than 25% of current global warming, with a warming potential up to 28 times greater than that of carbon dioxide (CO₂) (Sánchez-Santillán et al., 2024). Likewise, rice cultivation is responsible for 11% of agricultural emissions, and the main emitting countries in this activity are India, China, and the USA (OECD, 2022).

Agricultural management produces alterations in the soil, from changes in the microbiota to erosion, infertility, and increased GHG production, therefore, the use of microorganisms has become very important in recent years, given their multiple benefits in agroecosystems, thanks to their interactions they are capable of regulating the absorption of nutrients in plants, promoting growth, improving resistance to different pests and pathogens, reducing soil contaminants, among others (Hartmann & Six, 2023; Kumar et al., 2019; Pathak et al., 2022).

Agroecosystems usually reduce the carbon present in the soil and release reactive nitrogen into the water and atmosphere, however, due to the high importance of these systems for global food security, there are many challenges in establishing sustainable techniques and management (Kallenbach et al., 2019).

Recently, various alternatives have been proposed, among which biocontrol and biofertilizers stand out. In the latter, various microorganisms have been used thanks to their benefit and influence on vegetative development. They are usually found in the spermosphere, the rhizosphere, and the phyllosphere and perform functions closely related to the ecosystem, facilitating the biogeochemical cycles of nutrients and minerals (Kashyap et al., 2023; Kumar et al., 2019).

4.2 Agroecosystems in agriculture

Man has constantly sought to modify natural systems, completely altering them and even artificially creating new ones. An agroecosystem encompasses a very broad and complex context from an ecological perspective and can be defined as a system that has been modified by humans to meet food and economic needs (Paleologos et al., 2017; Sal, 2001), in which agricultural and livestock techniques are modified by ecological, organic and natural methods.

An agroecosystem is characterized by having energy sources available that increase the productivity of certain organisms, it has little diversity compared to natural systems and its control and maintenance are complex. There are several types today, some of which are described in Table 4.1

The establishment of sustainable agroecosystems represents an important challenge that must be managed in a multidisciplinary way for better functioning; this will allow for more balanced, sustainable, stable, and self-sufficient systems. Currently, the traditional agricultural system is in crisis, because it is socially and environmentally unsustainable by not presenting any benefit in the face of the great challenges of climate change by directly affecting the planet by depleting natural resources, biodiversity (Tuttonell, 2024) and by making excessive use of fossil energy, synthetic fertilizers and chemical products (Frison, 2016).

In agriculture, the effects of climate change and the excessive use of chemicals in the process have caused infertile and degraded soils, therefore, currently, ecological strategies are being sought to be implemented such as composting, biofertilizers, and

Table 4.1 Types of agroecosystems.

Type	Definition	References
Grasslands	Grasslands cover a quarter of the Earth’s surface and have variable climatic conditions ranging from arid to humid. Their main impacts include overgrazing, the presence of fires, and the use of fertilizers.	Lok (2010)
Monocultures	Monoculture refers to the cultivation of a single type of crop in agriculture, although this term also applies to farm animals when only one species of animal is raised. The intensive use of land through monocultures accentuates the effects of climate change by promoting soil degradation, particularly in coastal areas. The most popular today are cereals such as soybeans, trees such as eucalyptus and pine, sugar cane, and cotton. However, since they are all one crop species, it is easier for diseases and pests to spread, and although it is also easier to apply the corresponding phytosanitary products, there is a greater risk of their resurgence and even of generating resistance. Therefore, food may contain excess toxic chemicals.	Calvo (2016)
Polycultures	They consist of planting two or more plant species at the same time and in the same field at a distance defined by their characteristics so that association relationships are formed that benefit all the species planted and competition for resources is not produced. By planting different plant species within a crop field, biodiversity is positively influenced, not only with respect to monoculture as an alternative, but also due to the presence of microorganisms associated with each particular crop and the general balance achieved in relation to the accompanying flora and fauna through interactions.	Malca Lema and Tandapilco Tandapilco (2024)

(Continued)

Table 4.1 (Continued)

Type	Definition	References
Woody systems	Woody crops, including fruit trees, vines, and shrubs, are essential in agriculture for their economic and ecological value. Among the most notable are apple, olive, almond, and grapevine trees. These require specialized management due to their physical structure and long life cycle. Understanding their water, nutrient, and light needs is crucial for fruitful development and production. Pruning and disease management are vital, especially because of their woody structure, which is different from that of herbaceous crops.	Egea-Fernandez et al. (2015)

the use of microorganisms that favor their conservation ([Santillana, 2006](#)). The Green Revolution represented great demographic, social, and economic growth, but it also brought with it the use of chemical fertilizers and pesticides, as well as the development of crops that generated high harvest yields. However, climate change and the depletion of resources have caused these yields to be lower. Therefore, it has been described that agroecosystems can be an alternative to improve production efficiency and sustainability in agriculture ([Gaba et al., 2018](#)), while they can reduce erosion, and nutrient leaching and improve the efficiency of energy capture, which would translate into greater carbon availability, greater productivity, minimal losses and low environmental impact ([Sarandón, 2002](#)).

Faced with the current challenges posed by climate change, developed countries have sought to introduce more ecological systems, replacing, for example, chemical fertilizers with organic ones and more sustainable crops. However, in some cases, this specialization of agriculture has produced adverse conditions such as soil erosion and compaction and even the loss of biodiversity ([Caon & Vargas, 2017](#); [Ramachandran Nair, 2011](#)).

The benefits of agroecosystems require the proposal of more viable ecological systems; therefore, a redesign must be considered considering the benefits and also the requirements of the environment according to the current situation in order to make a more functional and sustainable system ([Rosati et al., 2021](#)).

4.3 Plant–microorganism interactions

The soil is a complex system in which its components perform important functions that contribute to its maintenance. It functions as a reservoir for multiple microorganisms that allow the fixation of essential nutrients for plants such as

nitrogen, forming structures of NO_3^- and NH_4 and eliminating ammonia, uric acid, and urea (Guzmán Duchén & Montero Torres, 2021). Microorganisms allow the development, growth, and health of plants, through a process of symbiosis in which photosynthetic metabolites such as phenolic compounds and flavonoids are released by the plant in conjunction with the cellular recognition of the microorganism (Calvo, 2011). It has been shown that microorganisms promote plant growth and development, through better assimilation of nutrients, and the production of plant hormones known as phytohormones (Singh et al., 2011) such as indole acetic acid, auxins, gibberellins, cytokinins, among others. Beneficial microorganisms or plant growth-promoting bacteria (PGPB) not only favor the development and success of the plant but also increase its protection against pathogens, abiotic stress, droughts, etc. (Bécquer et al., 2017; Solanki et al., 2023). Likewise, the use of microorganisms allows reducing the use of chemical fertilizers without affecting crop yields and the vegetative quality of the crop. Various studies on the plant-microorganism interaction have focused especially on mycorrhizae, where some bacteria such as *Azospirillum halopraeferans* and *Bacillus amylolyquefasciens* reduced the negative effect of salinity on the species *Prosopis chilensis*, improving seed germination, considering the use of microorganisms as a reliable biological method that can contribute to soil fertility (Villegas-Espinoza et al., 2014). Among the most studied microbial genera are *Pseudomonas*, *Enterobacter*, *Bacillus*, *Variovorax*, *Klebsiella*, *Burkholderia*, *Azospirillum*, *Serratia*, *Azotobacter*, and *Trichoderma* (*Hypocrea teleomorph*) (Dohrmann et al., 2013; Kumari et al., 2022), which have been attributed the ability to protect the plant by stimulating the immune system against pathogen attacks (Valenzuela-Ruiz et al., 2019), as well as in the synthesis of plant hormones called phytohormones, which are responsible for regulating the growth and development of the plant (Borjas-Ventura et al., 2020). There is a wide variety of phytohormones in plants, where the most studied are auxins, cytokinins, gibberellins, abscisic acid, and ethylene, widely used in agriculture to promote rooting and germination of seeds, as well as harvest yields and fruit quality, however, further studies are required in the use of these in specific crops as well as the use of bioregulators in conditions of abiotic stress, especially water and thermal stress, which are factors significantly affected by climate change (Borjas-Ventura et al., 2020).

4.4 Effect of climate change on plant-microorganism interactions

Microorganisms in plants are mainly found in the roots, these are transferred to the soil, air, and water, and even to the fauna present (Rudgers et al., 2020). It has been pointed out that they can modulate the tolerance of plants to climate changes such as drought, temperature, salinity, and abiotic stress, in the same way plants increase their capacity to use nutrients (Busby et al., 2016). Therefore, it can be considered that beneficial microorganisms can be an alternative to the resistance and survival of plants in the face of current climate change.

The use of microorganisms (bacteria and fungi) as biofertilizers in plant development has been of great interest in recent years, where a positive effect on the success of agricultural crops has been evident. Beneficial bacteria, also known as growth promoters, do not invade plant tissue as fungi do, they can colonize the root very effectively and positively influence its growth (Rueda-Puente et al., 2009).

Microorganisms are essential technological tools to achieve stability and improve the productivity of an agroecosystem. Their use in agriculture is potential because they allow for greater decomposition of organic waste in the soil, elimination of toxins, reduce the prevalence of diseases, promote the production of hormones, and provide essential nutrients (Çakmakçi et al., 2006).

PGPB act through two mechanisms: (1) directly when their metabolites are used as growth regulators in the plant, (2) indirectly when their produced metabolites function as antagonists, involving aspects of biological control, suppressing or inhibiting the growth of microorganisms harmful to plant development, among others (Rueda-Puente et al., 2009). Microorganisms in the soil are responsible for carrying out up to 90% of the biological processes in the soil (Bajsa et al., 2013), however, their benefits on the soil are diminished by the negative effects of poor agricultural practices, as well as by factors such as climate change, since these produce alterations in the chemical and physical properties of the soil, as well as in the functional availability of nutrients (Ibarra-Villarreal et al., 2021). The consequences of climate change have forced microorganisms to adapt, migrate, evolve, and/or become extinct (Hoffmann & Sgrò, 2011; Hutchins & Fu, 2017). Although they can reproduce at a faster rate than macroscopic organisms, there are limitations such as the dispersion factor, dependence on other species (association), and the environment (Archer et al., 2019; Brum et al., 2015). Understanding the mechanism of adaptation and response of microorganisms to climate change is complex, therefore, it must be considered further studies that quantify and interpret the responses of microorganisms to environmental changes and sources of stress linked to climate change (Cavicchioli, 2019; Webster et al., 2018).

4.5 Conclusions

Climate change is promoted by activities such as agriculture, which produces up to 29% of total GHG emissions, which demonstrates the importance of promoting more sustainable agroecosystems. However, this represents a significant challenge that must be managed in a multidisciplinary way to produce more balanced, sustainable, stable, and self-sufficient systems. Currently, the traditional agricultural system is in crisis due to the excessive use of fossil energy, synthetic fertilizers and chemicals. Therefore, strategies such as the use of microorganisms represent an ecological and modern alternative. Microorganisms allow the fixation of essential nutrients and favor the development, growth, and health of plants in agricultural crops. Their use allows reducing the use of chemical fertilizers without affecting crop yields and vegetative quality, as well as the negative effect of salinity, which is why it can be considered a reliable biological method. However, further studies are required on the use of these

in specific crops, as well as the use of bioregulators in conditions of abiotic stress, especially water and thermal stress, which are factors significantly affected by climate change.

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An agroecological perspective for climate-smart agriculture

5

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5.1 Introduction

Climate change has a significant impact on food production, affecting both the quantity and quality of crops. Rising temperatures and more significant variability in precipitation result in lower agricultural yields, especially in tropical and warm regions where adaptive capacity is more limited (Licker et al., 2013; Mirón et al., 2023). While rising CO₂ concentrations could theoretically benefit some crops, such as rice, by increasing yields, the adverse effects of extreme temperatures and extreme weather events, such as droughts and heavy rains, often outweigh these benefits (Hasegawa et al., 2013; Moriondo et al., 2011). Furthermore, food quality is also affected, with decreased concentrations of essential nutrients, such as proteins and minerals, in many crops (Fernando et al., 2012; Myers et al., 2014). Therefore the intersection between climate change and food production represents a critical challenge for global food security.

Ecological farming systems, such as agroecology, can play a crucial role in mitigating the impacts of climate change by promoting sustainable practices that improve the resilience of agricultural systems. One of the main contributions of these farming systems is the promotion of biodiversity, which helps to increase the resistance of crops to pests and diseases, reducing the need for chemical inputs and, consequently, greenhouse gas (GHG) emissions associated with their production (Altieri et al., 2018). In addition, crop rotation, using green manures, and composting improve soil health, increasing its carbon sequestration capacity and reducing erosion (Gattinger et al., 2012; Mirón et al., 2023).

Furthermore, studies indicate that organic farming systems can emit up to 40% less carbon than conventional agriculture (Krauss et al., 2020). Furthermore, ecological agriculture promotes efficient water use and conservation of water resources, which is especially important in a climate change scenario that predicts more significant variability in precipitation (Pimentel et al., 2005).

In this sense, another important concept in mitigating the impacts of climate change on agriculture is climate-smart agriculture (CSA), which can significantly contribute to mitigating the effects of climate change through an integrated approach that seeks to increase agricultural productivity, improve the resilience of farming communities and reduce GHG emissions. CSA promotes agricultural practices that increase the efficiency of resource use, such as water and nutrients, allowing farmers to obtain higher yields without expanding the cultivated area, which is crucial to avoid the conversion of natural lands into agricultural areas, leading to environmental degradation and biodiversity loss (Taylor, 2018; Tittonell, 2014). In addition, CSA encourages the adoption of techniques that help farmers adapt to climate change, such as crop rotation, the use of more resistant plant varieties, and the implementation of agroforestry systems, increasing the resilience of crops to extreme weather events and maintaining soil health and biodiversity. CSA also focuses on reducing GHG emissions associated with agriculture by improving soil management and reducing the use of chemical fertilizers, which are responsible for significant emissions, in addition to integrating agroecological practices that contribute to carbon sequestration in the soil (World Bank, IFC, MIGA, 2016).

Thus, agroecological systems are highly related to CSA, being a fundamental tool in searching for resilient agricultural systems to climate change. This chapter will address how agroecological practices can contribute to mitigating the impacts of climate change on agricultural systems.

5.2 Agroecological perspective

Agroecology is an approach that encompasses ecological, social, and economic perspectives in the search for sustainable ecosystem development, food system transformation, and climate change mitigation. As it is understood as a science, a set of practices, and a social movement, agroecology has applications on the farm, in the field, and throughout the food system (Rosset et al., 2019; Wezel et al., 2009).

The implementation of agroecological principles, listed as input reduction, recycling, biodiversity, soil quality, animal welfare, economic diversification, connectivity, synergy, participation, social values, land and natural resource governance, justice, and co-creation of knowledge, is fundamental to the expansion of agroecology. In this sense, agricultural systems are developed according to the ecosystem and social context, and different farming practices can be applied to meet these principles (Wezel et al., 2020).

Agroecology aims to mitigate damage to the ecosystem through these agricultural practices. An example is using biological agents to reduce pests and improve soil quality. In this way, this production matrix enables the production of high-quality food while simultaneously preserving the environment. This model promotes ecological balance and ensures the maintenance of the land's productive capacity in the long term without depleting it, generating the maintenance of local biodiversity and meeting the principles of agroecology (Wezel et al., 2020).

Since these practices are based on soil fertility as one of the ways to combat erosion, techniques such as proper management, crop rotation, replacement fertilization, and conservation of organic matter are adopted, which result in greater productivity and maintain soil fertility, desertification is prevented by keeping the soil covered with plants and leaves during cultivation, acting as a sponge that protects the soil and retains water. In addition, the agroecology production matrix employs crop rotation and intercropping, as well as green manures, organic compounds, and ground natural rocks to prevent pests, diseases, and invasive plants (Wezel et al., 2020).

The other essential pillars linked to this form of cultivation, in addition to biodiversity, are nutrient cycling, encouraging the use of composting to reduce the use of external inputs, the integration of different agricultural components, such as plants, microorganisms, and animals, where we can mention the agroforestry system, which integrates trees and shrubs in agrarian crops, improving the efficiency of the resources present, and sustainability, which aims to balance the economic, social and environmental spheres (Altieri & Nicholls, 2020).

5.3 Elements of an agroecological approach from a climate-smart agriculture perspective

Technology is essential in helping humanity better manage the biosphere and implement an inclusive circular economy in terms of resources. Therefore it is expected that the synchronization of agricultural sensors, actuators, AI, and remote sensing will enhance the operation of the circular ecosystem, a factor that can expand sustainable agriculture. In biological science, there are possible applications in the genetic editing of drought-resistant crops or new antibiotics, which are tools used to include, remove, or remodel an organism's genome. These technologies, added to an exponential understanding of plant systems' biology, change how new crop varieties are created (Kumar Goel & Vishnoi, 2022; Lacey, 2021).

Similarly, for agroecology to interact with environmental preservation, interdisciplinarity must interact with natural, applied, and social sciences, engineering and landscape ecology, biology, and computational technology to expand the scope of traditional agronomy. Thus, regenerative agriculture, with few inputs, can boost crop productivity. However, achieving the sustainable level required by global and national food production systems is only part of the scope of food security. Primary social, political, technical, and economic conditions must be complemented to ensure affordable access to healthy nutrition (Vishnoi & Goel, 2024).

Farmers have historically diversified their planting techniques to better adapt to climate change, especially in emerging countries (Nyasimi et al., 2017). Likewise, agricultural practices are constantly changing to optimize livestock and crop production, including improved forage, crop varieties and animal breeds, water conservation technologies, and soil and land management methodologies (Azadi et al., 2021). In small-scale agriculture with few resources, climate-saving agriculture (CSA) technologies are expected to enhance adaptive capacity access to food and promote climate change mitigation (Hellin & Fisher, 2019). Implementing CSA practices and technologies alone or in combination can significantly minimize the adverse effect of climate variability on the agricultural environment (Akhter Ali, 2017).

Currently, some studies on equipment used in modern agriculture, such as drones for spraying, can contribute to expanding the smart agricultural ecosystem and mitigating climate change. However, studies on these technologies are generally conducted without considering the environment in which they are used. A multiple and efficient agricultural ecosystem is usually conditioned by physical conditions, such as agricultural machinery, division of labor, and organizational demands. In addition, specific issues such as location, user skills, insider attacks, and replicated data require innovative instruments for protection. Therefore research is essential before agricultural technology is implemented in the community (Gupta et al., 2020).

Therefore vulnerable-smart agriculture (VSA) has emerged alongside CSA, which are systems that place small-scale agriculture centralized in an interventionist program. These systems are considered intelligent because they have the following potential: predicting critical circumstances (climatic and agricultural) in agriculture and measuring their effects (see Table 5.1).

CSA is also defined as a modern agricultural system that can increase yields, deal with climate extremes, and contribute to climate change solutions.

In the sphere of CSA, the production factors and efficient management methodologies are improved after the harvest (Chandra et al., 2018). Using modern agricultural techniques, CSA aims to increase production, adapt, and minimize GHG emissions (World Bank, 2011). In addition, this system is different from the usual methods because it helps to strengthen the organization of the activities of farmers in the private, social, and political sectors, to contribute to the adaptation of the production system and efficiency in the use of resources (Lipper et al., 2014). Within the three pillars of CSA, food adequacy and food security are agricultural development's main objectives in climate change (Rosenstock et al., 2016).

Table 5.1 Differences between climate-smart agriculture and vulnerable-smart agriculture.

Perspective	Efficiency	Mitigation	Adaptation	Function for farmers
CSA	Intensifies results. Amin et al. (2015)	Discusses the consequences of climate change. FAO (2017)	Optimization of input application. Makate et al. (2016)	Seeks change in policies based on increased income. Steenwerth et al. (2014)
VSA	Small-scale agriculture at the Center of Action Programs. Abegunde et al. (2019)	Consider the repercussions of climate change. Azadi et al. (2021)	It enables a flexible agricultural system. Fadina & Barjolle (2018)	Substantial changes will only occur if small farmers are active in normalization. FAO (2017)

CSA, Climate-saving agriculture; VSA, vulnerable-smart agriculture.

However, CSA methods are linked to factors that can potentially harm decision-making if not handled correctly. Thus, interested groups must collaborate to improve knowledge and make informed decisions (Brandt et al., 2017). Consequently, the number of criteria that must be considered when choosing and favoring CSA practices in specific locations can lead to complexity and uncertainty (Greene et al., 2011). Furthermore, quantitative and spatially explicit data are essential to identify appropriate locations to target specific CSA practices (FAO and OECD, 2012). For example, the database must include social, economic, and biophysical determinants of small farmers' agricultural vulnerability to climate change, enabling a demand-based approach such as VSA.

There is an urgent need to value the role of small-scale farmers and provide them with technical information and instruction on the most appropriate practices for managing planting, harvesting, and storage, as well as improving knowledge exchange between farmers. Furthermore, small-scale farmers must be informed so that they adopt agricultural practices in response to climate change. The careful study of these methodologies and assessing farmers' practices should be prioritized to establish and integrate viable and practical solutions, ensuring they do not negatively impact any area.

More up-to-date services, such as mobile payment systems, which work even in rural areas, provide families with a new, practical, and secure way to manage their finances, even when geographically distant. In addition, the government and other policymakers must accurately distinguish between the objectives and capabilities of small and large farmers. Therefore a greater focus on new techniques that address the "farmer scale" issue and maximize their participation in using these technologies is essential to improve the initial CSA paradigm and provide a full version called VSA. In this way, the results of this study can be used to improve techniques and means of analysis, providing a starting point for further quantitative and qualitative studies (Azadi et al., 2021).

Another available technology is farm management information systems (FMIS), which aim to strengthen agricultural and industrial production models. The model was created to support precision agriculture, enabling work with changes in resource management parameters and improvements in the economic practice of products (Wang et al., 2006). The information system includes various instruments that aim to obtain, edit, and disseminate operational information related to environmental and agricultural changes (Zhang & Pierce, 2013). The sensor network is divided into collector nodes or access points with full capabilities and source nodes with reduced capabilities.

Generating ecological food at a reduced cost is the central objective of agroecological resource management information systems. Different agricultural productions in Australia (Merrill, 2010), China (FAO and OECD, 2012), Western Europe (Lawson et al., 2011), and America (Gutierrez et al., 2014) use such practices and constitute an example to be followed by those seeking progress today.

5.4 Application of agricultural practices within the concept of climate-smart agriculture

When dealing with CSA, the concept of sustainable agriculture must be taken into account since this is defined as an integrated system of both plant and animal

production practices that meets human needs and aims to improve environmental quality through the efficient and conscious use of natural resources, integrating biological cycles and controls when deemed appropriate, in addition to the efficient use of nonrenewable resources, to promote economic viability and improve the quality of life of society as a whole (Keeney, 1990; Muhie, 2022). Therefore agricultural practices that involve such principles and aim to increase agricultural productivity sustainably, make it resilient to climate change, and mitigate GHG emissions are desirable (Lipper et al., 2014; Saj et al., 2017).

Therefore principles such as the laws of nature, biotechnological combinations, and consolidated agricultural practices are indispensable when using CSA. Some examples include agroforestry, biological control of pests and diseases, crop rotation, integrated nutrient management, and cover cropping, among other practices that will be explored below (Abegunde et al., 2019; Keshavarz & Sharafi, 2023).

- **Agroforestry**

The agricultural practice that combines forest species with crops and animals is a form of CSA and is widely used, as it enables carbon sequestration. In these systems, carbon can be stored in aboveground reservoirs by trees, shrubs, grasses, and herbs, and below-ground through the soil itself, roots, and rhizomes, which corresponds to about 20%–26% of the total biomass and, therefore, considered a vital carbon reservoir (Handavu et al., 2021; Houghton et al., 2009; Sambou et al., 2024).

According to the IPCC Land Use Report, among all land use methods analyzed, agroforestry has the most significant potential for carbon sequestration due to the large portions of areas that are susceptible to land use in agroforestry cultivation (Verchot et al., 2007). In addition to helping to mitigate GHG emissions, agroforestry contributes economically to farmers concerning crop losses due to natural phenomena caused by climate change. Combining forest species cultivation with cultivars allows the soil and the ecosystem to adapt to such phenomena, especially concerning high temperatures and drought scenarios.

Therefore agroforestry can contribute to the regulation of hydrological cycles since the deep roots of trees can travel through a more significant portion of soil and, hence, transport a substantial volume of water and nutrients (Lasco et al., 2014; Stetter & Sauer, 2024; Verchot et al., 2007). Furthermore, according to Verchot et al. (2007), the use of this integrated system allows for increased soil porosity, reduced runoff, and increased soil coverage by increasing infiltration and water retention, in addition to increasing evapotranspiration rates. This helps to keep the soil aerated and remove excess water more quickly than other cropping systems.

- **Crop rotation**

Crop rotation is an already established agricultural practice that helps reduce GHG emissions. The practice, which involves regularly alternating crops, allows for improved soil health and nutrient cycling, reducing the use of chemical inputs during planting (Kumar et al., 2024).

Crop rotation of crops such as corn and cereals with legumes or broadleaf crops benefits the physical and chemical properties of the soil, such as water conservation and nitrogen availability (Gan et al., 2015; Wang et al., 2020). In addition, using this practice allows plants to resist diseases since, due to crop rotation, the cycle of the pathogen originating from a specific family is interrupted by the change of crop and, consequently, its reduction in the soil (Shah et al., 2021).

Furthermore, crop rotation also reduces the proliferation of weeds in plantations. Due to the selection pressures caused by rotation, the practice acts as a filter, preventing a particular weed species from establishing itself in the soil affecting the seed bank (Mishra et al., 2022; Nichols et al., 2015).

- **Cover cropping**

Among the different forms of CSA, cover cropping increases soil carbon and benefits the ecosystem (McClelland et al., 2021; Rehberger et al., 2023). Following crop rotations, cover cropping is also considered one of the primary forms of harmful GHG emissions in agriculture and can reach a mitigation potential of around 500 million tCO₂-^{eq} (McClelland et al., 2021).

Cover crops can be grown together with the main crop or during fallow periods between crops, and the biomass produced by these crops is not harvested, acting as green manure in the field. However, according to McClelland et al. (2021), for cover crops to act efficiently, especially in carbon sequestration, soil preparation, sowing, and planting time must be considered, as they can affect the quality of crop residues. The quantity and quality of residues must be considered when using this agricultural practice, as they directly influence organic matter and the amount of nitrogen in the soil. For example, leguminous cover crops act in nitrogen fixation, while nonleguminous crops increase soil carbon sequestration and help reduce nitrogen leaching (Sadra et al., 2024).

- **Biofertilizers**

In addition to already consolidated agricultural practices, biologically based products have been widely explored. The inappropriate use of chemical fertilizers, in addition to contributing to the emission of GHGs, harms terrestrial and aquatic ecosystems, causing the depletion of soil nutrients and reducing biological diversity (Chataut et al., 2023).

Given this, biologically based products have been studied for their application in the field due to their advantages. Biofertilizers, also called microbial inoculants, are recognized for the beneficial properties offered to plants to promote growth, such as nitrogen fixation, phosphorus solubilization, production of growth hormones, nutrients that provide resistance to plants, in addition to improving soil fertility (Just et al., 2024).

Therefore due to the numerous mechanisms of action of the microorganisms that make up biofertilizers, they also end up contributing to the storage of carbon in the soil, either directly through the application and renewal of microbial inoculants or indirectly through plant growth through nutrient solubilization (Just et al., 2024; Kholssi et al., 2022). The use of autotrophic microorganisms that live in the soil as biofertilizers can act in the biogeochemical cycle of carbon, nitrogen, and oxygen, in addition to fixing carbon dioxide, and resulting in an increase in the amount of carbon in the soil (Just et al., 2024; Karl et al., 2002).

- **Biological control of pests and diseases**

Biological pest control is a management strategy that uses living organisms to reduce pest populations, aiming to minimize crop damage. This approach may involve the introduction of natural enemies, such as predators, parasites, or pathogens, that act on target pests, promoting ecological balance. Biological control is considered a sustainable alternative to chemical pesticides, contributing to reducing environmental impacts and promoting biodiversity (Heimpel et al., 2013; Lamichhane et al., 2016). Furthermore, this practice can be integrated into agricultural management systems, such as sustainable and CSA, to increase crop resilience to climate change and pest pressure (Murage et al., 2015; Mwongera et al., 2017).

Biological pest control plays a crucial role in CSA. This approach reduces reliance on chemical pesticides, minimizing environmental impacts and human health risks while improving biodiversity and soil health (Furlong & Zalucki, 2017). Furthermore, biological

control can help mitigate the effects of pests that become more prevalent due to global warming, contributing to food security in a climate change scenario. Integrating natural enemies into pest management not only improves crop productivity but also promotes the adaptation of agricultural practices to new climate conditions, aligning with CSA goals of increasing productivity and resilience while reducing GHG emissions (Howden et al., 2007; Neufeldt et al., 2013).

Similarly, biological disease control aims to combat microorganisms that cause crop diseases using other organisms. This strategy has shown great promise and the enormous potential of using antagonistic agents to combat plant diseases. In general, the composition of these products tends to be less complex. It can often be produced on-farm, giving producers more freedom and allowing for more sustainable agricultural ecosystem management (Collinge et al., 2022).

Therefore biological control of pests and diseases is aligned with the objectives and principles of CSA, in addition to supporting ecological management, allowing the power of agents that cause significant agricultural losses every year.

5.5 Challenges and limitations of the climate-smart agriculture methodology in agroecology

CSA was developed to incorporate the issues raised by climate change into planning and investment processes in the agricultural sector. Although CSA focuses on three fronts: policies, institutions, and financing, the major bottleneck is not signaling which agricultural practices are considered climate-smart. In other words, there is no master plan for CSA, which is a limiting factor in expanding this concept. The implementation of this innovation will depend on the specific conditions of the place where it is to be implemented. Still, among the practices included in CSA, we can mention genetically modified organisms, GHG management, biofertilizers, and application of agroecological concepts (Saj et al., 2017).

One of the challenges of this practice is the development of policies based on scientific evidence. This would be the first step towards creating criteria for the functioning and development of CSA. At this point, the scientific community has a critical role since scientific research will enable more assertive and secure decision-making, with a better understanding of the phenomena involved in the CSA process, to provide the population with reliable and comprehensive results. There seems to be an impasse between science and the creation of public policies in this sector, and this makes sense when we look at the scenario in which food security is seen as a private good provided by a farmer but also as a public good managed by the government, which implies that the issue should be assessed in a much more comprehensive way (Lipper et al., 2014; Saj et al., 2017).

Promoting transition and implementation actions for CSA are also necessary to assist farmers. Studies report the adoption of some practices that have a positive impact on the implementation of CSA, some of which are GHG mitigation, reforestation, carbon sequestration, organic production, use of bio inputs and genetically modified organisms (Hrabanski & Coq, 2022; Lipper et al., 2014).

CSA suggests synergies and trade-offs should be made between food security and impact mitigation to reshape policies in response to climate change. Public-private finance, including climate finance, is also needed to support transition and innovation in this sector (Lipper et al., 2014).

Mobilizing financial investment is also a challenge in this scenario. Identifying and analyzing the costs of climate-smart strategies compared to conventional ones can help strengthen efforts in agricultural development, which would be a source of climate finance. Adapting agrarian systems will require greater initial investment, while identifying and crediting mitigation benefits generated through the adaptation process could increase financial resources (Lipper et al., 2014).

The most significant limitation of this scenario is that the concept of CSA is still under construction and continues to be refined. The scenario is promising; however, these practices must be significantly promoted to achieve the expected levels of food security within sustainable agriculture (Wakweya, 2023). Furthermore, farmers' adaptation needs to be a goal within these CSA practices, as they are the primary agents affected by these changes. Still, they are also the most interested in the subject, as it affects their lives. In addition, CSA requires requests on local and global scales in the short and long term. Several fronts must be addressed together, expanding from the local to the international, which is undoubtedly highly complex. Such complexity also occurs due to the uncertainties associated with the results of climate models (Zhao et al., 2023).

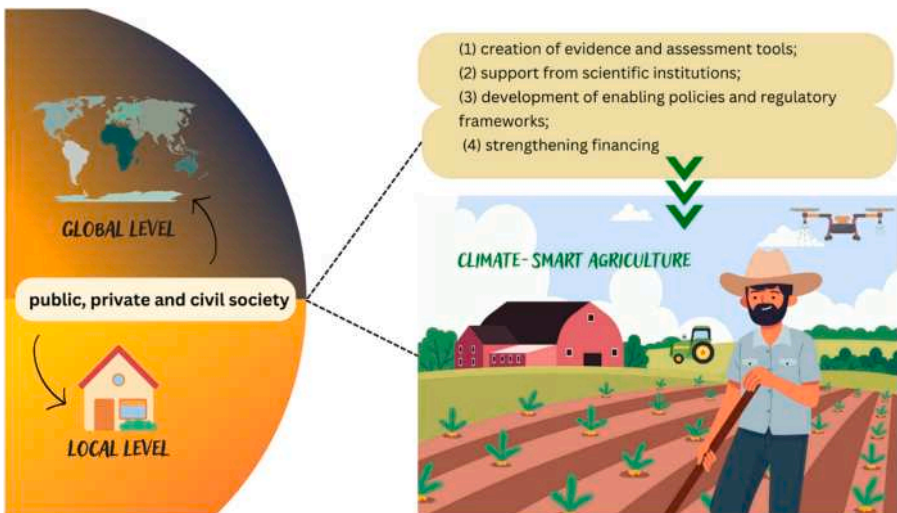


Figure 5.1 Combined action by stakeholders (public, private, and civil society) at local and global levels towards implementing climate-smart agriculture. This image was produced using the graphic design tool Canva, and the images were taken from Freepik, a website that provides free images. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

According to the Intergovernmental Panel on Climate Change (IPCC), human activities are causing challenging changes in global agricultural and food production, culminating in the difficulty of establishing sustainable development for CSA. GHG emissions are causing a massive imbalance in the farming ecosystem, which could result in scarcity of water resources and their uneven distribution and climate variability, such as extreme droughts and precipitation exceeding forecasts. All this variability alters the functioning of the ecosystem, such as distributions of light, heat, water, and other agricultural climate resources, resulting in possible reductions in agricultural production, income, and food insecurity (Zhao et al., 2023).

Finally, Fig. 5.1 illustrates that joint action is needed by stakeholders (public, private, and civil society) at local and global levels on fronts such as (1) the creation of evidence and assessment tools, (2) support from scientific institutions, (3) development of enabling policies and regulatory frameworks; and (4) strengthening financing, so that CSA has an accurate and practical implementation (Lipper et al., 2014). Therefore, estimating the supply and demand of agricultural resources under the scenario of constant climate change becomes increasingly relevant for the development of CSA.

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Climate change: a challenge for postharvest management, food loss, food quality

6

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6.1 Introduction

Global warming can be considered a central theme in global environmental discussions today, as it is a sensitive and crucial issue for human balance and subsistence. Climate change is the alteration of weather patterns over a prolonged period, which can be attributed to anthropogenic modifications in the Earth's atmosphere. Scientists have long highlighted the severe climate changes occurring on the planet and the environmental and socioeconomic effects of this constant change. It is a fact that temperatures have been gradually rising year after year, to the point that 2023 will be the hottest year on record, according to the World Meteorological Organization, with 2024 having the potential to surpass these thermal data.

Furthermore, the increased frequency and intensity of extreme weather events, storms, prolonged droughts, and changes in precipitation patterns are immediate impacts of global warming, as well as threatening factors such as greenhouse gas emissions, including increased concentrations of carbon dioxide (CO₂), nitrous oxide

(N₂O), methane (CH₄), depletion of the ozone layer (O₃) and deforestation (Bhatta et al., 2015). The environmental imbalance generated by the destruction of ecosystems can be considered one of the main consequences of climate warming, thus causing a considerable decrease in production due to the scarcity of raw materials, energy sources, and water, favoring the reduction of food security in terms of quantity and quality for future generations.

Agriculture is currently one of the main economic sectors most impacted by the drastic climate changes that have been occurring. Over the last century, there has been an observed increase in the average temperature of the Earth's surface, reaching approximately 0.74°C. By 2050, climate change is expected to have a detrimental influence on at least 22% of the area cultivated for the most essential crops. In addition to harming agricultural production, severe climate change directly impacts food prices, production costs, and the economy through variations in supply and demand. This recent climate instability has drastically altered these scenarios, compromising crops and thus impacting food production. In a general context, short- and long-term temperature variations, mainly due to inconsistencies in precipitation and lengthening of droughts, can lead to changes in crop growth and yields. Due to its large field of correlations and its fragility concerning meteorological variations, the impacts of climate change on agriculture have significant social and economic consequences (AJADIKE, 2017). Furthermore, the risk of agricultural losses is directly linked to excessive weed growth, pest and disease infestation, water availability, soil alteration, high production costs, and fires, among others, and these, in turn, have negative repercussions on the quality and quantity of products and, mainly, on food security (Cramer et al., 2017).

One of the most significant effects regarding the potential impacts of climate change on food security was in 2015–16, due to the famous natural phenomenon *El Niño*. This atmospheric change caused increased temperatures in 51 countries, affecting around 5.9 million children underweight (Campbell, 2022). Examples like this show the close relationship between climate change, adverse effects on agricultural production, and food security in guaranteeing the world population nutritionally sufficient food (Ahmed et al., 2023).

Since more than a quarter of food is destroyed or wasted in postharvest processes, meeting the high global demand for food has become a major, worrying, and commercial challenge for nations. Therefore finding promising tools to minimize postharvest losses, especially in underdeveloped countries, has become a topic of investigation in scientific research, thus aiming at medium and long-term strategies to mitigate these losses and, consequently, create an environment favorable to safer food and to meeting Sustainable Development Goals 2, which aims to end hunger and guarantee access for all people to healthy, nutritious and sufficient food. To guarantee more effective food security, aiming at equal access to safer and more nutritious foods that meet the population's needs, it was necessary to incorporate smart agrotechnologies and practical postharvest management activities, such as pre-cooling, refrigerated storage and transportation, drying and dry storage, storage in a controlled atmosphere, regulated ripening, growth-regulating chemicals, exposure to ozone, UVC irradiation, heat treatments, and other technologies provide high-quality food for consumers throughout

the year and reduce postharvest losses during marketing, to reduce the effects of adverse weather conditions on agriculture. Climate-smart agriculture is a promising and essential line of research for this sector since it refers to agricultural strategies that increase production and profitability for farmers, thus helping them adapt to the negative consequences of climate change and consequently reducing the loss of food quality (Leisner, 2020; Owino et al., 2022).

This chapter aims to understand the main risks generated by climate change in agriculture and the consequent impacts on quantitative and qualitative losses in the food supply, thus directly affecting food security. Within the current climate scenario, this discussion is particularly relevant because it deals with issues that are sensitive to human sustainability, as well as the development of technologies aimed at adapting to new agricultural ecosystems, efficient operations in postharvest management, and reducing food loss during processing, clearly aiming to increase food production, with a focus on income and food security.

6.2 Adaptation to new agricultural ecosystems

The evolution of the terrestrial ecosystem over geological eras offers a representative view of climate change and how it affects biosphere adaptations. Initially, it was dominated by unicellular organisms and simple colonies; later, the emergence of sulfur-reducing bacteria and the development of photosynthetic pathways laid the foundation for the evolution of complex life. From 0.8 billion years onwards, the first fossil records emerged, in addition to molecular evidence and biomarkers that indicate the evolution of more complex organisms, culminating in the Cambrian explosion, when skeletonized organisms appeared (Planavsky et al., 2021).

The stratigraphic records show the evolution of marine and terrestrial ecosystems, from non-vascular plants to vascular and seed-bearing plants, in addition to the emergence of forests. During the Paleocene epoch, approximately 56 million years ago, the “Paleocene-Eocene Thermal Maximum” occurred, a 4°C–8°C increase in global temperature that persisted for 0.1–0.2 million years, causing the extinction of 35%–50% of deep-sea benthic foraminifera and changes in the distributions of terrestrial plants and animals. This initial warming is thought to have abruptly released 3000–7000 Pg of carbon and methane hydrates into the deep sea, acidifying the oceans, shallowing the calcium carbonate compensation depth, and raising sea levels by up to 15 m. This climate change parallels the current human-caused increase in atmospheric CO₂, but the current release rate is about ten times greater. In 2014, carbon release from anthropogenic sources reached about 10 PgC/year, raising concerns about the potential triggering of large amounts of carbon release from methane hydrates due to anthropogenic warming.

The Pliocene era was marked by the so-called “Mid-Piacenzian Warm Period”, when atmospheric CO₂ concentrations may have reached around 400 ppm, similar to current levels. During these periods, the average global surface temperature was 2°C–3°C higher than pre-industrial Holocene levels, and sea levels were 10–20 m higher (Steffen et al., 2016). This explains possible climate scenarios, such as the end

of the 21st century, where contemporary warming could lead to sea level rises of 10 m or more (Clark et al., 2016).

The Quaternary Period reveals periodic and well-defined glacial and interglacial states, with regular transitions modulated by astronomical factors. These records indicate a tight coupling between temperature and greenhouse gas concentrations, with critical feedback processes leading to tipping points. Despite abrupt climatic oscillations, the biosphere maintained relatively stable extinction rates until the megafaunal extinctions at the end of the Pleistocene and the beginning of the Holocene, caused by the interaction between climate change and human migration, as described in

The Earth's atmosphere has evolved steadily from volcanic and glacial eras to the beginning of the Anthropocene, a period characterized by intense human influence on the planetary system. This interval, which began in 1750, is considered a new geological period within the current interglacial era known as the Holocene. Human influence on a global scale is evident through indicators such as forest deforestation, greenhouse gas emissions (CO_2 and CH_4), and changes in global temperature.

Agricultural activity is responsible for a substantial proportion of global greenhouse gas emissions, around 19%–29%, in addition to playing a significant role in freshwater consumption and contributing 31% to the decline in wild biodiversity. In this spectrum, a link is formed between human activities of food cultivation, animal husbandry, and resource management with the natural environment through interaction with soil, water, and air. Thus, unsustainable agricultural practices of deforestation, soil degradation, water pollution, and biodiversity loss lead to an imbalance. However, despite the points presented, the crucial role of agricultural systems and sustainable production in food security stands out, as they ensure an adequate supply of food in quantity and quality. Considering its importance, sustainable production is a viable solution (Lynch et al., 2021).

6.3 Postharvest management

Postharvest management includes several steps: cleaning, washing, selection, classification, disinfection, drying, packaging, and storage. Additionally, these practices involve managing and controlling variables such as temperature and relative humidity, selecting and using packaging, and applying complementary treatments such as fungicides (Janghu et al., 2024).

In this era of postharvest agricultural losses caused by changes in climatic conditions, the integration of climate agrotechnologies and efficient postharvest management operations is necessary as an alternative measure to increase food production income and to mitigate the effects of adverse climatic conditions on agriculture (Gautam et al., 2017). Constant variations in precipitation patterns, inconsistent and adverse weather conditions, high temperatures, and alarming increases in atmospheric levels of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) and other variables inevitably result in changes in temperature and humidity over time,

producing significant food losses and degradation. The causes of postharvest food losses differ between fresh and dry products. For fresh products, such as fruits and vegetables, inadequate temperature management increases the speed of ripening and softening, the development of decay, and water loss. Low relative humidity in the environment increases water loss, leading to physical damage, increasing ethylene production, accelerating ripening and senescence, and favoring spoilage (Bradford et al., 2018; Kumar & Kalita, 2017).

For dry products, such as grains, wet periods cause the grains to absorb more moisture than ideal during storage periods. The increase in moisture content promotes the growth of fungi and molds, thus resulting in significant losses in stored grains, since fungal contamination of dry foods reduces the value of the commodity for the market and often makes the product inedible and even toxic, as it becomes favorable to the development of mycotoxins, which are dangerous to human health (OSUJI et al., 2020). In addition, high temperatures increase the risk of fire in crops and encourage shorter life cycles, as well as being a favorable environment for breeding insects and pests that can affect crops and stored grains (Wester et al., 2019).

This critical issue has led to the search for practical actions to incorporate climate-smart agrotechnologies and effective postharvest management activities to reduce the effects of adverse weather conditions on agriculture, productivity, and stored products. Climate-smart agriculture is a way of transforming the primary agricultural production techniques to offset the adverse effects of climate change and, consequently, increase agricultural productivity (Agrawal et al., 2021), in addition to being a strategy that increases production and profitability, helping farmers adapt to the severe negative consequences of climate change, thus reducing the effects of climate change, such as carbon sequestration in the soil or reducing greenhouse gas emissions (Subedi et al., 2019).

6.4 Reducing food loss during processing

Proper food waste management represents a growing environmental, economic, and social sustainability challenge. Understanding the definitions and classifications of food loss and waste is essential to developing practical solutions and prevention policies that minimize the negative impact of this global problem. According to the FAO, food loss is the decrease in food quantity or quality throughout the supply chain, from production to consumption. In contrast, food waste refers to what occurs during the production, postharvest, and processing stages (FAO, 2016).

Food waste classification involves categories that require specific management methods. Common approaches distinguish between avoidable and unavoidable waste, with subcategories for different types of food and stages of the product life cycle. For example, WRAP classifies food waste into avoidable (such as bread slices, apples, and meat), possibly avoidable (such as bread crusts and potato peels), and unavoidable (such as meat bones, pineapple skins, and tea bags).

The European Commission categorizes food waste into three groups: food losses, unavoidable waste, and avoidable waste. These classifications are crucial for

identifying critical points in the supply chain where interventions can be implemented to reduce waste. The factors influencing food loss and waste vary significantly based on countries' economic development levels. In developed countries, most waste occurs during consumption due to the generation of food surpluses and consumer behavior. In contrast, in developing countries, waste is prevalent during production due to limitations in agriculture, inadequate harvesting techniques, lack of efficient storage systems, inefficient transportation infrastructure, and limited technology investment. This information is essential to identify critical points in the supply chain and apply appropriate interventions to reduce waste.

New emerging technologies have significant potential to mitigate food waste. These technologies include chemical and mechanical preservation to extend the shelf life of food, information and analysis systems for forecasting and monitoring, and processing solutions to transform fresh food into finished products. Established technologies, such as crop monitoring systems and sorting machines, have proven applications in the industry. Innovations such as drones with sensors for remote monitoring and cameras with advanced software to analyze crop conditions are showing promising effectiveness.

Nanotechnology applied to precision agriculture is another important innovation that helps reduce input waste and improve crop health, optimizes the use of resources, and promotes more efficient harvests. Digital technologies, such as mobile devices and sensors, have also proven effective in identifying and reducing food losses. Global positioning systems and radio frequency identification help to optimize distribution routes, reducing product spoilage during transportation. Digital simulations are used to predict and mitigate problems in the supply chain, and digital tracking systems, such as blockchain, offer a more precise and transparent view of production practices.

In addition, vertical farming, despite its high initial cost, can significantly reduce food waste by shortening the time needed for harvesting and delivery to market. This technology allows food to be grown in controlled environments and closer to urban centers, minimizing the time and costs associated with transportation (Helliwell & Burton, 2021).

6.5 Development of new ingredients from co-products

Postharvest management is essential to reduce losses between harvesting and distributing food, especially fruits and vegetables (Janghu et al., 2024). However, unpredictable weather patterns affect food cultivation, reducing the quantity and quality of crops. In this context, the food processing industry is essential in reducing losses by improving postharvest systems. All food processing generates waste. This waste can be used to make the food industry more sustainable.

The great challenge is to make waste processing economically viable. An alternative to reducing food loss during processing is developing new ingredients from co-products. These by-products can be used to obtain flavors, odors, pigments,

polysaccharides, and proteins with technological functions, in addition to biopesticides and biofuels.

A growing increase in the cultivation of pitaya fruit (*Hylocereus* spp.) has been observed in Brazil, mainly in the Southeast and Northeast regions. Consequently, the processing of this fruit is encouraged (Rabelo et al., 2020). One of the residues of this processing is the peel, which can be seen as a by-product. The Pitaya peel is rich in phytochemicals with great potential for application in the food industry, so it is a potential by-product (Carvalho et al., 2022; Mai, Tran, LE, 2022). Pitaya peel is just one example, as fruit processing waste represents a significant loss of nutrients with high biological value and a considerable volume that implies severe environmental risks (Patel et al., 2016). The industries that transform grapes into wine generate a large volume of organic by-products rich in bioactive compounds such as antioxidant fibers (Machado et al., 2017). This by-product is of growing industrial interest for economic, environmental, and sustainability reasons (ferrer-Gallego, Silva, 2022). In the literature, this by-product is sometimes called bagasse, which is composed of peels and seeds, and rarely by the peduncle that was not removed before extracting the grape juice, representing approximately 20% of the total volume of processed fruits (Denny et al., 2014; Bordiga, Travagllia, Locatelli, 2019). In addition to the feasibility study of by-products, studies aimed at improving food processing unit operations are essential. For example, infrared heating can replace conventional heating in the industry as an effective method for processing food under similar conditions (heating time, heat transfer coefficient, and energy expenditure) (Abdelbasset et al., 2022).

6.6 Food quality and safety with climate change

With the current and predicted effects of climate change in the world, there is a clear need to ensure an adequate and safe food supply to protect human rights, as the United Nations (UN) provides that every person has the right to adequate food for their health and well-being. Therefore ensuring the supply of safe food is essential to the protection of this declaration. However, climatological factors are described as long-term changes, representing an urgent threat to the ecosystems and human societies of our planet, as they imply an increase in global temperature and natural disasters such as droughts, hurricanes, tsunamis, and floods, which can affect agriculture, fishing, and livestock, directly or indirectly affecting food production worldwide.

Agriculture, which occupies almost 40% of the Earth's surface, is the sector most vulnerable to climate change, such as rising temperatures, prolonged droughts, high levels of CO₂ in the atmosphere and extreme precipitation. These changes influence microorganisms, insects, pests, and nonbiological factors such as air pollution and nutrient deficiencies. These affect soil quality, plant health, and crop productivity, increasing human exposure to mycotoxin and pesticide residues. Aflatoxin contamination, for example, is likely to increase

with climate change due to extreme events that affect soil quality and the availability of essential nutrients so that the interaction between soil, micro-organisms, and biodiversity loss can limit plant growth, altering arable areas and pests, requiring more pesticides and increasing human exposure to residues (Bahram et al., 2018).

In addition, climate change affects marine biomass, which is crucial for oxygen production and CO₂ fixation globally. Ocean warming favors the proliferation of harmful algae that produce toxins that harm human and animal health (du Pontavice et al., 2021). Heat stress mainly affects terrestrial animals, with a significant impact on those that produce milk, because when they are unable to release the heat generated by metabolism due to high temperatures and humidity, they face difficulties in maintaining internal balance, resulting in behavioral and physiological changes, which can be immediate, such as adjustments in cellular signaling, or prolonged, such as the production of heat shock proteins, and vary according to the species, breed and production phase. Infants are especially susceptible to this stress due to the high energy consumption for milk production, which can compromise both their productivity and udder health, increasing the incidence of mastitis (Wankar et al., 2021).

The increase in CO₂ concentrations and average temperatures is a crucial factor for vegetation growth, with an increase in harvests, thus presenting greater food availability for human health. However, other effects of climate change, such as heat waves, torrential rains, and extreme drought, can negatively influence harvests and food production (Mbow et al., 2020). Furthermore, an increase in temperature is related to the rise in foodborne diseases, which may be greater during the summer, when there are more cases of these pathologies in humans, causing harm to health (Jin et al., 2020).

Another aspect impacted by climate change would be food spoilage, since global warming, by raising temperatures by up to 4.9°C, affects the microbiological stability of nonrefrigerated processed foods, such as fruit drinks and evaporated milk, increasing the risk of growth of spoilage microorganisms and, consequently, the

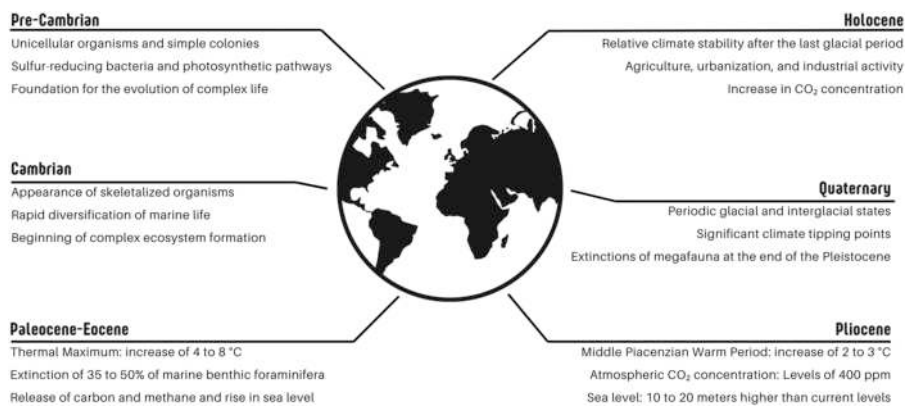


Figure 6.1 Flowchart of evolutionary periods of ecosystems.

Climate Change

Agriculture is highly vulnerable to climate change, which is driven by rising temperatures, prolonged droughts, and extreme precipitation. These climatic factors negatively impact soil quality, plant health, and crop productivity. As a result, there is an increased exposure to residues of mycotoxins and pesticides.



Agriculture

Climate change exacerbates aflatoxin incidence by disrupting soil quality and nutrient availability through extreme weather events. This impact limits plant growth, alters arable land, increases pesticide usage, and consequently leads to higher human exposure to toxic residues.



Animals

Thermal stress impacts dairy animals by causing difficulties in maintaining internal balance due to high temperatures and humidity. This stress leads to behavioral and physiological changes, including an increased production of heat shock proteins. Additionally, it raises the incidence of mastitis, adversely affecting both animal health and productivity.



Post-harvest food deterioration

Rising temperatures and extreme climatic events compromise the microbiological stability of non-refrigerated processed foods and dry grains. These changes increase the risk of growth for deteriorating microorganisms and fungi, leading to higher economic losses and elevated risks of fungal contamination.



Figure 6.2 Factors resulting from climate change for food security and food spoilage throughout the food chain.

potential for economic loss. In addition, extreme weather events, such as heavy rainfall and high humidity, favor the proliferation of fungi in cereal grains and bulk dry foods, exacerbating the risk of fungal contamination. The impact of climate change on food security is a complex issue with numerous diverse and interconnected factors, including food spoilage at stages of the food chain, which can be seen in [Fig. 6.1](#) Thus, preventive measures are necessary for food security, mainly in identifying the factors that impact food at all points and requiring a comprehensive, broad, and organized structure to address potential problems in food production ([Jin et al., 2020](#)) ([Fig. 6.2](#)).

6.7 Conclusions

Climate change and global warming are crucial issues for human balance and subsistence, discussed based on observing changes in climate patterns caused by human actions. Environmental imbalance results from the destruction of ecosystems and affects the production of raw materials and energy resources, reducing food security in quantity and quality. Agriculture, an important economic sector, is firmly and directly impacted by climate issues, leading to drastic variations in food prices and production costs. To ensure food security, it is essential to adopt smart agrotechnologies and improve postharvest management, adapting to new agricultural ecosystems and reducing losses during processing. Research is also needed to develop new ingredients from by-products. These measures are essential to ensure food quality and security in the face of climate change.

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Impact of plant growth promoting microorganisms on draught and salinity stress management

7

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7.1 Introduction

Recently changing climatic conditions or the rising global population emerged as a major challenge for food security. The changing climatic conditions or the rising greenhouse gases adversely affect agricultural productivity, environment, or human health. It is well known that plant is a sessile organism and currently facing significant risks from a variety of biotic such as phytopathogen attacks, and abiotic stresses such as draught, salinity stress, temperature, cold, heavy metals accumulation, etc. These biotic and abiotic stress factors significantly affect agricultural productivity and soil productivity. Although among various abiotic stresses, drought and salinity have emerged as a severe challenge for the growth and survival of plants worldwide (Wani, 2016a, 2016b).

Drought stress the most common abiotic stress recognized in the world that significantly affects plant survival (Manikavelu et al., 2006). It is well known that some of the major city of the world currently facing the challenges of water scarcity that also appears a major challenge for human survival. Although the drought stress is a worldwide problem, arid or semiarid regions are highly prone to this abiotic stress

(Lau & Lennon, 2012). The changing climatic conditions, uncertainty in rainfall, or the reduced groundwater level increases the challenges of drought stress. Similar to this salinity stress is also reported to their adverse impact on plant growth and agricultural productivity. According to the published report, currently approximately 20% of the total cultivated land faces the challenges of salinity stress. These stressors disrupt the normal physiological processes of plants, leading to suboptimal productivity and reduced yields or their prolonged exposure can lead to the death of plants. Moreover, these factors also alter the natural interactions between beneficial microbes (Patterson, 1995; Scherm and Coakley, 2003; Ziska 2010). Although to mitigate the stresses different traditional approaches have been followed but now a days utilization of beneficial microbial species including bacteria, fungi, actinomycetes emerges as one of the sustainable, economic and ecofriendly approach. Previously authors reported role of beneficial microbes in the mitigation of draught and salinity stress management. Gong et al. (2023) used *Rhizophagus irregularis*, *Exophiala pisciphila* strain to mitigate the challenges of draught stress in the maize. The PGPM inoculation significantly enhance the draught stress and also improved the photosynthetic activity and root hydraulic properties of Maize. Similarly Al-Karaki & Al-Raddad (1997) used Arbuscular Mycorrhizal Fungi (AMF) for the mitigation of draught stress in wheat. In case of salinity stress, (Mousavi et al., 2022) reported about the *Azotobacter* species which after inoculation mitigate the salinity stress in *Glycyrrhiza glabra* L.

The current chapter has been compiled to briefly discuss the challenges and impact of drought and salinity stress, on the growth and yields of plants and how PGPMs mitigate the challenges of draught and salinity stress

7.2 Impact of drought and salinity stress on plant

The advent of draught adversely affect the growth and productivity of plants, during the every stage of their growth (Zeid & Shedeed, 2006). Draught condition also affect the plants morphological and physiological attributes or even the prolong draught condition lead to death of the plants. In the previous study, authors reported the impact of draught stress on the various stages of the growth (Harris et al., 2002; Kaya et al., 2006). Khan et al. (2019) reported significant reduction in the germination and growth of rape seed under the drought. Batool et al. (2022) also reported adverse impact of draught on the seed germinating and seedling growth in *Brassica napus*. Similarly Okcu et al. (2005) reported impaired growth of seedling in the pea under drought stress conditions.

Plants growth and development directly dependent upon the cellular differentiation or division. However the draught condition significantly alter the turgor pressure due to water deficiency, which led to the impaired the growth and differentiation of plant cell (Taiz and Zeiger 2006). Addition to this under the stress condition, the reduction in water availability also impaired the nutrient uptake potential of plant. The lesser water availability in the roots not be able to transport the nutrients (Farooq, Wahid, Kobayashi, Fujita, Basra 2009; Garg, 2003). These factors ultimately affect the yield

of crops or plants. Previously authors reported about the negative impact of drought on crop yields (Garg, 2003; Grossman & Takahashi, 2001; Peuqe et al., 2002). For example (Nayyar et al., 2006) observed 45%–69% reduction in yield of chick pea after the advent of draught stress similarly; Martínez et al. (2007) observed 58%–87% reduction in yield of common pea during draught stress condition. Kawakami et al. (2006) reported 13% reduction in potato yield during the draught stress. Moreover the prolong stress conditions also affect the transpiration rate, stomatal resistance or canopy temperature of the plants (Siddique et al., 2001).

The adverse impact of draught also reported reduction in photosynthesis. Draught stress also reported for their impact on decresaement in the leaf expansion (Bota et al., 2004), which negatively affect the leaf morphology which disrupt the chlorophyll pigments resulting reduction in photosynthesis (Cornic and Massacci 1996; Wahid & Rasul, 2005). The exposure of draught stress to the plants lead to the generation of reactive oxygen species such as O^- , H_2O_2 , OH^- these anions radicals are highly reactive in nature and reacts with other biological molecules including the proteins, lipids, or nucleic acid, results in degradation of cell membrane integrity or damage the nucleic acid (Fazeli et al., 2007; Parihar et al., 2015).

Similarly salinity is another severe abiotic stress that appear as a major challenges to achieve food productivity. Advent of salinity adversely affects the crop production at any growth stages and their effect on plants varies on duration and extent of salinity (Atta et al., 2023; Verma et al., 2021). The advent of salinity negatively impact the plant growth via impairment in water uptake by the plant roots, which resulted in the poor growth and seedling germination. Previously authors reported adverse impact of salinity on seed germination. For example Akbarimoghaddam et al. (2011) reported poor seedling growth in wheat, Xu et al. (2011) reported poor growth in rice, Ulfat et al. (2007) also reported lower seedling growth in *Brassica* spp. In addition to lowering water potential, salinity also causes ion imbalance, ion homeostasis disruptions, and toxicity. This changed water status results in a reduction in initial growth and a limiting of plant productivity. At the overall plant level, the negative impact manifests as plant mortality or a decline in productivity. According to Greenway and Munns (1980), salinity also affects oxidative stress and generates various types of reactive oxygen species similar to those generated during drought stress. These reactive oxygen species are highly reactive in nature and react with the biomolecules and disrupt the integrity of cell membranes, nucleic acid, etc. (Gomes-Filho et al., 2008; Khan & Rizvi, 1994). However, another severe effect of salinity is the imbalance in nutrient uptake, the presence of saline conditions, the imbalance of the turgor pressure, and disturb the water uptake by the roots. These disturbances also severally affect the photosynthetic pathways or photosynthetic activity or ultimately plant growth (Gomes-Filho et al., 2008).

7.3 Plant growth promoting microorganisms in abiotic stress management

Plant interacts with a diverse range of both pathogenic or beneficial microorganisms. The microbial species including bacteria, fungi, actinomycetes that play detrimental

or significant roles in enhancing plant growth are termed as plant growth-promoting microorganisms (PGPMs). These PGMS regulate the plant growth by different mechanisms such as phosphate solubilization phytohormone modulation, ammonia production, etc. Additionally also protects the plant from pathogen invasion by secreting bioactive compounds, antibiotic production, HCN production, etc. (Kumar, et al., 2018; Sharma et al., 2024).

Advancement in omics technology has illustrated that plant system is associated with millions of taxonomically diverse microbial communities as a result of a continuous process of co-evolution between the host and the associated microbes. These host–microbe interactions colonized in the various ecological niche in the form of the rhizosphere, phyllosphere, and endosphere are termed as “phytomicrobiome.” These phytomicrobiome employ a diverse mechanism to mitigate abiotic stresses on crop health or agricultural productivity via the production of antioxidants, modulation of phytohormones such as auxin, cytokinins, and detoxification of health hazardous. For example, the rhizosphere inhabiting rhizobacteria stimulates indole acetic acid production that promotes root or plant growth (Zhang et al., 2022). Similarly, microbes associated with the phyllosphere and endosphere adapt certain strategies accompanied by phytohormones modulation and metabolite secretion, enabling plants to survive under stress conditions (Fadiji et al., 2023; Gupta et al., 2020; Kumar, et al., 2018; Kumar & Verma, 2018; Singh et al., 2018, 2023).

In the last two decades, the severity of draught or salinity stress significantly enhanced throughout the world and the research community continuously works to mitigate the challenges of these stresses in sustainable ways. In this regard we have carried out a bibliometric data study to evaluate the significance of plant growth promoting microorganism or plant microbiota in abiotic stress management. In the bibliometric data study, we retrieved 2317 published articles between 2004 and 2024, in which plant–microbes interact in abiotic stress management. However to describe the significance, we have downloaded the data from the Scopus database by searching the keywords “Plant microbiota,” OR “Plant growth promoting microorganisms,” OR “plant microbes interaction,” AND “abiotic stress,” or “salinity” or “draught,” or “pH” or “water stress” or “oxidative stress” or “rhizosphere,” or “plant growth promotion” or “microbes” or “endophytes,” or “AMF” and created the bibliometric analysis (Fig. 7.1) using VOS viewer processing software (v1.6.9). The different colors present in the network showed linked terms, however, the size of the labels showed the number of publications, and the distances present between two nodes represent the degree through which they are associated (Fig. 7.1).

7.4 Plant growth promoting microorganisms in drought stress management

Recent studies indicated that drought stress is one of the severe challenges for plant growth and survival and currently, it affects 9%–10% of cereal production (Lesk et al., 2016). Drought stress significantly reduces the soil fertility indicators like microbial biomass and extracellular enzyme activity and also affect the physiology of

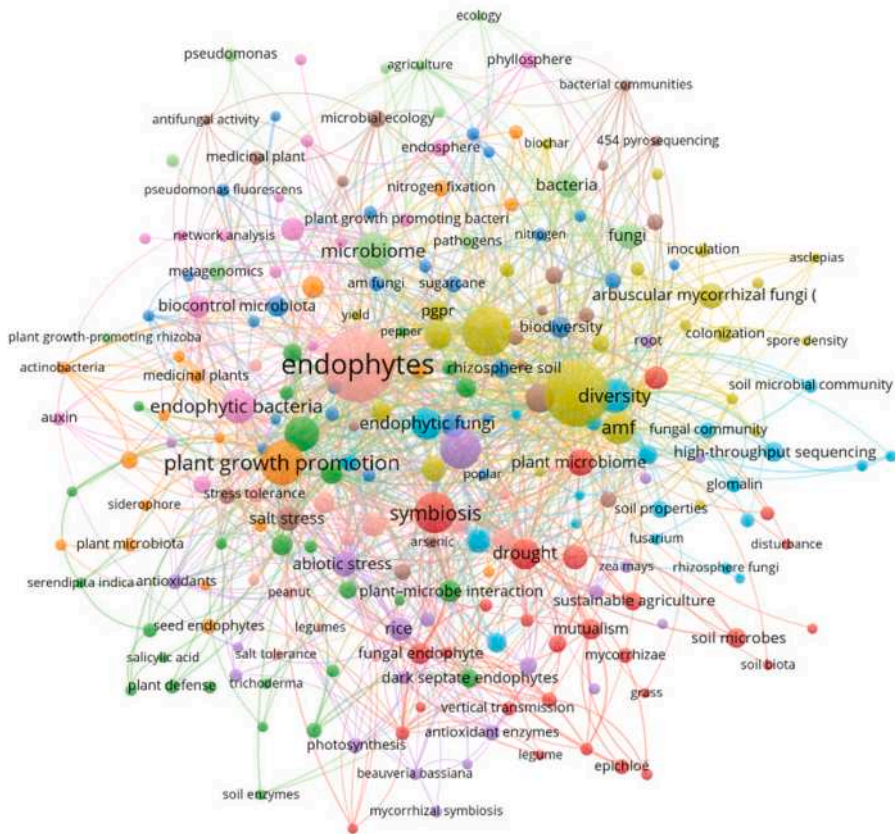


Figure 7.1 Network visualization map displaying the key term present in the title and abstract of the published article related to the plant–microbe interactions in abiotic stress management. Nodes of the same color showed clusters of interconnected phrases, however, the circle size indicates the number of publications larger the size indicates a large number of publications. The network has been created using the software VOS viewer processing software (v1.6.9.).

plants (Qu et al., 2023; Vurukonda et al., 2016). Furthermore, some microbes failed to adapt to extreme condition, hence reduced soil microbial community is also reviewed (Bogati & Walczak, 2022). However, some beneficial microbes like PGPR or fungal species help the plant to adapt under severe water scarcity condition. These mechanisms include phytohormone modulation, root morphology via differentiation of adventitious and lateral roots, osmolytes accumulation such as proline, glycine betaine, and antioxidants volatile organic compounds and exopolysaccharide (EPS) production (Hussain et al., 2014; Iqbal et al., 2022). In the last few years, various authors used PGPMs to mitigate drought stress, details are described in Table 7.1.

Unlike PGPR, inoculation of endophytes like *Piriformospora indica* employs drought tolerance through ROS sequestration with increased activities of antioxidant

Table 7.1 Impact of microbial inoculation on draught stress management.

Strains	Inoculation effect	Plant	References
<i>Rhizophagus irregularis</i> , <i>Exophiala pisciphila</i>	Draught stress management and enhance maize growth, photosynthesis, root hydraulic properties	Maize	Gong et al. (2023)
<i>Acaulospora morrowiae</i> , <i>Paraglomus occultum</i> , <i>Funneliformis mosseae</i> , <i>R.clarus</i> , and <i>R.intraradices</i>	Draught stress management	Tomato	Alam et al. (2023)
<i>Rhizophagus irregularis</i>	Draught stress management	Soybean	Begum et al. (2023)
Arbuscular mycorrhizal fungi (AMF)	Draught stress management	Wheat	Al-Karaki and Al-Raddad (1997)
	Improve the growth, water status, and nutrient uptake	<i>Cinnamomum migao</i>	Xiao et al. (2023)
<i>Funneliformis mosseae</i> , <i>Rhizoglopus intraradices</i> , <i>Diversispora versiformis</i>)	Draught stress management	<i>Zenia insignis</i> seedlings	Zhang et al. (2019)
Bacillus	Draught stress management	Plant	Vivas et al. (2003)
Grümberg	Draught stress management	Soybean	Grümberg et al. (2015)
AMF	Draught stress management	wheat	Mathur et al. (2019)
<i>Penicillium minioluteum</i> , AMF	Draught stress management	<i>Chenopodium quinoa</i>	González-Teuber et al. (2018)
AMF	Draught stress management	Damask rose	Abdel-Salam et al. (2018)
AMF	Draught stress management	Plants	Chandrasekaran (2022)
AMF	Draught stress management	Marigold	Asrar and Elhindi (2011)
<i>Glomus mosseae</i> (Gm) or <i>Glomus etunicatum</i> and <i>Bradyrhizobium japonicum</i>	Draught stress management	Soybean	Aliasgharzad et al. (2006)

enzymatic increase of catalase and glutathione in rice (Tsai et al., 2020) and *Microdochium majus*, *Meyerozyma guilliermondi*, and *Aspergillus aculeatus* in drumstick (Javed et al., 2022). Endophytes are another plant-associated microbial symbionts that remain asymptotically within the plants' tissue and offer plant tolerance against harsh conditions like drought (Verma et al., 2021). Some endophytes like *Bacillus* sp. LZR216 is known for the modification of the root system in *A. thaliana* through auxin signaling, promoting lateral root growth which improves the water absorption potential of plant roots (Wang et al., 2015). Liu and Wei (2019) corroborated the similar findings under drought stress and suggested that dark septate endophyte fungi significantly modulated root morphology accompanied by hormonal regulation.

7.5 Plant growth promoting microorganisms in salinity stress management

Likewise, drought stress and salinity stress also adversely affect the root architecture and extent of root exudate production. This changes ultimately affect the composition and function of microflora of the plant (Khanna et al., 2022). Previously various authors reported the deleterious effect of salinity growth and also on the plant-associated microbiota (Berens et al., 2019). Li et al. (2021) reported a significant impact on the abundance of microbial communities in Cucurbitaceae family. However, the author found an abundance of *Pseudomonas* in both salt-sensitive and tolerant plants. Xu et al. (2020) reported salt stress led to enhancement in some specific bacterial group like Acidobacteria and cyanobacteria and reduction in the *chloroflexi* and *Actinobacteria* in the groundnut rhizosphere. Similarly, (Yaish et al., 2016), enhancement in the abundance of Enterobacter species under the salt stress condition in *Medicago truncatula*.

Although in the previous studies, it have been confirmed that rhizosphere associated PGPR respond to salinity stress by adjusting osmotic concentration with the production of proline, glycine and other osmoprotectants (Ali et al., 2022; El-Esawi et al., 2018). Salinity also affects uptake of major nutrients such as N, P, and K, which results in the huge reduction in crop yields. Phosphate solubilizing rhizobacteria like *Bacillus pumilus* make the availability of phosphorus in the rhizospheric soil, resulting increased root and shoot dry weights of *Zea mays* (Mukhtar et al., 2020). Similarly, siderophore producing *Pseudomonas pseudoalcaligenes* and *Bacillus subtilis* significantly contribute Fe accumulation in roots and to its transportation to leaves (Sultana et al., 2021; Yasmin et al., 2020). Apart from all these, microbe-mediated activation of ionic transporters of HKT also helps in providing salt tolerance in plants. Experiment with *Arabidopsis thaliana* revealed that *Bacillus megaterium* ZS-3 induces ion homeostasis by down-regulation of HKT1 and the up-regulation of NHX1 and AVP1 gene, which mediate crucial role in pumping H^+ into vesicles, which results in acidification and generate a H^+ gradient and enable plants to better respond against the elevated level of salinity (Shi et al., 2022). (Rabhi et al., 2018) reported inoculation of *Pseudomonas*

knackmussii MLR6 (PGPR) induce the up regulation of SOS genes in *A. thaliana* grown in salt stress condition. Details of other PGPMs used for the salinity stress management are described in [Table 7.2](#).

Table 7.2 Impact of microbial inoculation on salinity stress management.

Strains	Inoculation effect	Plant	References
Microbial consortia	Salinity stress management	Tomato	Kapadia et al. (2021)
<i>Azotobacter</i> sp.	Salinity stress management	<i>Glycyrrhiza glabra</i> L	Mousavi et al. (2022)
<i>Curtobacterium albidum</i>	Salinity stress management	Paddy plants	Vimal et al. (2019)
<i>Nocardioide</i> s sp	Salinity stress management	Wheat seedling	Meena et al. (2020)
<i>Rhizobium</i> –AMF	Salinity stress management	<i>Phaseolus vulgaris</i>	Garcia et al. (2019)
PGPMs	Salinity stress management	Wheat	Singh and Tiwari (2021)
<i>Alternaria chlamydosporigena</i> , <i>Paraphoma chrysanthemicola</i> , <i>Bipolaris sorokiniana</i>	Salinity stress management	<i>Artemisia ordosica</i>	Hou et al. (2021)
<i>Rhizobium laguerreae</i> , <i>Rhizophagus irregularis</i> , and different combination of <i>Bacillus</i> sp.	salinity stress management	<i>Lathyrus cicera</i> .	Gritli et al. (2022)
Endophytic strains	salinity stress management	<i>Thymus roseus</i>	Mohamad et al. (2022)
<i>Rhizobium</i> , <i>Stenotrophomonas maltophilia</i>	salinity stress management and enhanced nodulation	Chick pea	Abd-Alla et al. (2019)
<i>Trichoderma</i> sp.	salinity stress management and enhanced photosynthesis	Wheat	Oljira et al. (2020)

7.6 Conclusion and future perspective

As it is well known that draught and salinity stress disrupt the normal physiological processes of plants, leading to suboptimal productivity and reduced yields or their prolonged exposure can lead to the death of plants. The utilization of beneficial microbial species including bacteria, fungi, actinomycetes emerges as one of the sustainable, economic and ecofriendly approach for the abiotic stress management. PGPMS under drought conditions, promote water uptake, improve root architecture, and produce osmolytes that help in maintaining the cellular turgor and metabolic activity. Similarly, in saline environments, PGPB mitigate ionic and osmotic stress by regulating ion homeostasis, producing EPSs, and inducing antioxidant enzyme activity to reduce oxidative damage.

Isolation and characterization of microbial strains is the primary step in microbiological study but after so much advancement in omics and next generation sequencing still researcher community largely dependent upon the cultivable techniques. But large number of strains still not be cultivated in the laboratory conditions, which limit the actual information of plant –microbiome study.

Although till large number of microbial strains have been isolated from different source to use as plant or soil inoculants to mitigate the salinity and draught stress challenges. But the surviavality and adaptability of the strains in the field conditions still appear as a big challenge. Additionally for the successful mitigation of abiotic stress challenges, it has been suggested that microbial strains which will further use for the mitigation strategies, should isolate from the plants growing at that particular habitat.

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Abatement techniques for greenhouse gases and ammonia emissions from livestock farms and a computational software

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8.1 Introduction

The agricultural sector, specifically livestock farming, plays a substantial role in the release of greenhouse gases (GHGs) and ammonia (NH_3) into the atmosphere (Ferraz et al., 2024). The primary source of these emissions is the management of manure, which involves storing it in tanks outside the barns or underground pits within the housing buildings. GHGs, such as methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), as well as NH_3 , present significant environmental challenges (de Vries et al., 2023). They are responsible for exacerbating climate change, causing air pollution, and contributing to the degradation of ecosystems. Mitigating these emissions is vital for attaining environmental sustainability and meeting progressively stricter environmental regulations (Bruhwiler et al., 2021; Chataut et al., 2023).

Livestock farming is a crucial component of worldwide agriculture, supplying vital commodities such as meat, milk, and wool. Nevertheless, the ecological impact of this sector requires the creation and execution of efficient methods to reduce pollution (Balafoutis et al., 2017). In recent years, there has been an increasing focus on sustainable manure management strategies aimed at reducing GHGs and NH_3 emissions (Chojnacka & Moustakas, 2024). These approaches involve modifying the physical, chemical, and biological characteristics of manure in order to reduce emissions during its storage and management (Kovačić et al., 2022). For example, methods like anaerobic digestion not only decrease CH_4 emissions but also generate biogas, which may be utilized as a sustainable energy source (Duan et al., 2020). Composting can effectively stabilize organic matter in manure, resulting in a reduction in both CH_4 and NH_3 emissions (Alengebawry et al., 2022).

Effective manure management is crucial for mitigating environmental consequences and ensuring the well-being and productivity of livestock. Efficient manure treatment can greatly diminish the emission of noxious gases into the atmosphere, thus aiding in the improvement of air quality and the mitigation of climate change (Kabange et al., 2023). This manure treatment technique utilizes a combination of biological, chemical, and physical methods to stabilize the manure, thereby decreasing the microbial activity responsible for GHG emissions (Samoraj et al., 2022). This technique offers a solid and effective solution for the sustainable management of manure by optimizing the conditions for anaerobic digestion and including additives that prevent NH_3 volatilization (Sousan et al., 2023).

Furthermore, a prototype biological chemical filter (BCF) functions as a comprehensive treatment technology for the exhaust air emitted by livestock buildings (Guo et al., 2022). The purpose of this filter is to eliminate a range of contaminants, such as various sizes of particulate matter (PM), hydrogen sulfide (H_2S), NH_3 , and N_2O , using a multistage procedure (Van der Heyden et al., 2020). Deploying such filters can significantly enhance the air quality within and in the vicinity of livestock facilities, thereby improving both the environmental conditions and human well-being. The filter functions through four discrete stages: dust elimination, gas absorption, biological treatment, and chemical scrubbing (Kumar et al., 2022). Every stage is carefully designed to specifically target pollutants, guaranteeing that the discharged air meets strict air quality regulations (Guo et al., 2022).

In addition to these physical abatement techniques, there are desktop software programs that can calculate the emissions of GHGs, such as CH_4 , N_2O , NO , CO_2 , and NH_3 , from dairy barns that are naturally ventilated (Laubach et al., 2024). Such software is a valuable tool for farmers, researchers, and policymakers as it provides accurate emissions data that can be used to inform management practices and ensure compliance with regulations (Ghassemi Nejad et al., 2024). The software utilizes sophisticated algorithms and up-to-the-minute data inputs to simulate the emissions in different operational scenarios (Hempel et al., 2022). The software allows users to simulate the effects of various manure management and ventilation strategies, aiding in the identification of the most efficient measures for reducing emissions (Niloofar et al., 2023). This computational tool not only improves the precision of emissions reporting but also facilitates the creation of customized mitigation plans that are in line with environmental sustainability objectives (Costantino, 2023).

This chapter aims to provide an in-depth overview of the existing knowledge of emissions from livestock farms, the environmental consequences of these emissions, and the different measures that can be employed to reduce them. The chapter also examines the fundamental concepts and practical uses of sustainable methods for managing manure, technology for treating air pollution, and computational tools. This chapter attempts to contribute to the creation of sustainable agricultural systems that can meet the needs of a growing population while reducing their impact on the environment.

8.1.1 Manure treatment

Livestock manure is a significant contributor to the release of NH_3 emissions, as well as being a notable source of GHGs, particularly CH_4 and N_2O , and NH_3 emissions have a role in increasing the acidity levels of water, soil, and ecosystems. GHGs, such as carbon dioxide and CH_4 , increase the Earth's temperature by trapping heat in the atmosphere. This phenomenon, known as the greenhouse effect, is responsible for global warming, which in turn leads to climate change. The organic materials in manure are decomposed by the bacteria, which leads to the emission of these gases. These bacteria would be inhibited by increasing the acidity of the manure, which could be achieved by reducing the pH. The pH value of the manure can be regulated to mitigate these gaseous emissions. Manure emissions of CH_4 , N_2O , and NH_3 may be mitigated by increasing its acidity (Samer, 2013).

Inorganic acids are feasible but have several drawbacks; for example, they can be soil pollutants. The use of organic acids is an effective but expensive method. Consequently, it is feasible to employ biowaste from the lemon, citrus, and milk industries, which naturally contain organic acids. Some studies have investigated the reduction of gaseous emissions from livestock manure through the use of various materials; however, they were determined to be soil pollutants. On the other hand, some attempts have been made in the prior art to reduce CH_4 , N_2O , and NH_3 emissions from livestock manure through inhibition of microbial activity using various inorganic acids as well as organic acids, resulting in lower levels of gaseous emissions (Samer, 2015).

8.1.2 Exhaust air treatment

Livestock production is a major contributor to the release of NH_3 , CH_4 , H_2S , CO_2 , N_2O , dust, volatile organic compounds (VOCs), and smells. NH_3 emissions are a significant factor in the acidity of water, soil, and ecosystems. The majority of NH_3 emissions, 95%, are a result of agricultural output, while 75% come from animal production facilities, including cattle and poultry. Furthermore, NH_3 is transported into the atmosphere and deposited in various ecosystems. However, CH_4 and N_2O are GHGs that contribute around 13% and 5% to global warming, respectively. Livestock production accounts for the majority (50%–70%) of CH_4 and N_2O emissions. Farm animals in the cattle business also have a significant impact on emissions and efforts to reduce them. Approximately 50% of NH_3 emissions and the overwhelming majority of CH_4 emissions in the agricultural sector are attributed to animal production (Samer & Abuarab, 2014; Samer, 2016).

Most studies focused on quantifying the emissions of NH_3 and GHGs. Besides, some studies have examined reducing NH_3 and GHG emissions from livestock buildings. On the other hand, some attempts have been made in the prior art to reduce emissions of NH_3 , H_2S , N_2O , CH_4 , CO_2 , dust, VOCs, and odors from livestock barns through the use of biofilters, resulting in lower levels of gaseous emissions. However, further development of biofilters is still needed, as a typical biofilter traps only 50% of emissions (Samer, 2016). Emissions from naturally ventilated livestock barns are highly dependent on the indoor air velocity as well as the outdoor wind velocity (Fiedler et al., 2013), where the measurement of air exchange rates in naturally ventilated livestock barns is uncertain (Samer et al., 2014) and leads to inaccurate quantification of gaseous emission (Samer et al., 2011a, 2011b). Besides, the building design, including ceiling height, has a significant effect on indoor air circulation and movement (Samer et al., 2017).

8.2 Problem statement

8.2.1 Manure treatment

The most important problems with the prior art can be identified as follows:

1. Reducing gaseous emissions from livestock manure is vital due to the environmental risks.
2. Poor efficiency of bacterial inhibitors.
3. Poor ability to inhibit microbial activity.
4. High costs of using various inorganic acids as well as organic acids.
5. Lack of interest in using biological waste (waste of agro-industries) to reduce gaseous emissions from livestock manure.

8.2.2 Exhaust air treatment

The most important problems with the prior art can be identified as follows:

1. Reducing gaseous emissions from animal production buildings is critical due to the environmental risks.

2. Poor efficiency of biofilters, as a typical biofilter traps only 50% of emissions.
3. A typical biofilter requires 420 m² of space outside the building.
4. The cost of establishing and operating a typical biofilter is high.
5. Lack of interest in developing biofilters.

8.3 Novelty statement

8.3.1 Manure treatment

The novel technique is based on reducing the emissions of harmful gases to the environment (GHGs and NH₃) from livestock manure by adding biowaste from agricultural industries. The method is based on adding acidic biological wastes from food industries to livestock manure, which raises the acidity of the manure by reducing the pH value, which leads to the inhibition of bacteria present in the manure that break down organic materials, resulting in the emission of these gases. Thus, raising the acidity of livestock manure reduces emissions of GHGs: N₂O CH₄; as well as harmful gases: NH₃. This technique also features the following:

1. High reduction rates of environmentally harmful gaseous emissions from livestock manure are induced by 348%, 58%, and 649% compared to the traditional method for CH₄, N₂O, and NH₃, respectively.
2. A practical method that is easy to apply on a large scale.
3. Environmentally friendly method.
4. An economical way to reduce gaseous emissions from livestock manure.
5. Increasing the efficiency of inhibiting microbial activity.

8.3.2 Exhaust air treatment

The innovative technology, which includes a method and a device, is based on reducing gas, odor, and dust emissions from animal production buildings by manufacturing and implementing a chemical biological filter. The technology is based on (1) manufacturing and implementing the chemical biological filter, and it consists of four stages: the first stage is a device for removing PM₅, PM₁₀, and PM₂₀ dust; the second stage is a sulfur removal unit consisting of chains in which bacterial colonies are cultured to remove H₂S. This unit captures H₂S and decomposes it into water and harmless sulfate. In the third stage, NH₃ and N₂O are removed by *Nitrosomonas* bacteria, which use them as an energy source for themselves and release nitrite as a byproduct. Nitrite is transformed into nitrate by Nitrobacteria, and Nitration by sodium at the end of this stage to produce sodium nitrate, a food preservative; (2) nanoparticles were prepared and then used to treat bacterial colonies where the nanoparticles replace the relevant heavy metal present in the coenzyme structure; This process increased bacterial activity. (3) Lasers were used to treat bacterial colonies, which stimulated cell division. Thus, the number of bacterial cells increased. This technology also features the following:

1. High reduction rates of environmentally harmful gas emissions of 4,059,194 to 170,820 kg CO₂ equivalent per year are induced from a typical 150-head dairy barn. Thus, the equivalent of 3,888,374 kg CO₂ equivalent can be saved.

2. A practical method that is easy to apply on a large scale.
3. Environmentally friendly device and method.
4. A feasible device and method to reduce gaseous emissions from animal production buildings.

8.4 Emissions abatement techniques

8.4.1 Manure treatment

The present invention is a method to minimize harmful gaseous (GHGs and NH_3) emissions from livestock manure by adding agro-industrial biowastes. The method is based on adding acidic agro-industrial biowastes to the manure, which acidifies the manure by decreasing its pH value. Consequently, acidifying the manure reduces the emissions of the GHGs: CH_4 and N_2O , as well as the deleterious gas: NH_3 . The technique may be concisely summarized as follows: the researchers treated dairy bovine excrement with acidic agro-industrial biowastes, such as whey and waste from the citrus and orange juice industries. Subsequently, the emissions of CH_4 , N_2O , and NH_3 were quantified using customized gas detection equipment consisting of several flasks and a multigas monitor. The results revealed that the gas emissions from manure treated with waste from the citrus juice industry were $13 \text{ g m}^{-2} \text{ day}^{-1}$ for CH_4 , $0.219 \text{ g m}^{-2} \text{ day}^{-1}$ for N_2O , and $2.523 \text{ g m}^{-2} \text{ day}^{-1}$ for NH_3 . The gas emissions from manure treated with waste from the orange juice business were $13.58 \text{ g m}^{-2} \text{ day}^{-1}$ for CH_4 , $0.223 \text{ g m}^{-2} \text{ day}^{-1}$ for N_2O , and $2.581 \text{ g m}^{-2} \text{ day}^{-1}$ for NH_3 . The gas emissions from manure treated with whey were quantified as 17.45, 0.279, and $3.063 \text{ g m}^{-2} \text{ day}^{-1}$ for CH_4 , N_2O and NH_3 , respectively. The control sample, consisting of a combination of manure and water, released gas fluxes of 58.21, 0.347, and $18.9 \text{ g m}^{-2} \text{ day}^{-1}$ for CH_4 , N_2O , and NH_3 , respectively. The study revealed that utilizing waste from the citrus juice business for manure treatment proved to be the most efficient method compared to other treatments that were examined. This approach allows for significant reductions in gas emissions from manure, with decreased rates of 348% for CH_4 , 58% for N_2O , and 649% for NH_3 compared to the control (Samer et al., 2021a).

This invention relates to a method for reducing emissions of environmentally harmful gases (GHGs and NH_3) from livestock manure by adding biowaste from agricultural industries. The method is based on adding acidic biological wastes from food industries to livestock manure, which raises the acidity of the manure by reducing the pH value, which leads to the inhibition of bacteria present in the manure that break down organic materials, resulting in the emission of these gases. Thus, raising the acidity of livestock manure reduces emissions of GHGs: CH_4 and N_2O ; As well as harmful gas: NH_3 . The production method can be summarized as follows (Samer et al., 2011a):

1. Collect acidic biological waste from agricultural industries (whey or waste from factories of lemon or orange juices) so that its natural pH is between 3.6 and 3.9 and place it in a nonmetallic tank, for example, a tank made of Plexiglas, that is, acrylic.

2. Collect livestock manure from dairy cow farms so that its natural pH is between 7.1 and 7.5, and place it in a concrete tank as in large commercial farms.
3. Prepare a tank made of Plexiglas (i.e., acrylic) suitable for aerobic treatment conditions, with openings for the waste to enter and the gas to exit.
4. Add acid biowastes from agricultural industries (whey or waste from factories of lemon or orange juices) to livestock manure at a ratio of 1:1 in the tank prepared in the previous step.
5. Mix manure and acidic biological waste from agricultural industries

A practical experiment was conducted to achieve this by manufacturing and implementing a set of tanks to study the effect of adding acidic biowastes from agricultural industries to livestock manure on emissions of gases harmful to the environment (GHGs and NH_3) compared to the traditional method. A push-pneumatic system was designed and implemented in this study (Fig. 8.1). The main experiment equipment consists of a set of Plexiglas flasks, a temperature control system, and a gas measuring system. A 2.2 L ($\text{Ø}=18$ cm) wide-necked Plexiglas (i.e., acrylic) flask was used and connected (only during measurements) to a tight-fitting Teflon cap and a gas outlet connected to a gas measuring device (Fig. 8.1). Each flask was fed 800 g of fresh manure mixed with 800 mL of acidic liquid waste from agricultural industries (whey or waste from making lemon or orange juices). The temperature was controlled using a thermostatic water bath and was maintained at $38^\circ\text{C} \pm 0.3^\circ\text{C}$ to simulate the harsh weather conditions, where gas emissions increase with increasing temperatures. The concentrations of CH_4 , N_2O , and NH_3 were measured using an infrared photoacoustic analyzer (gas meter) once daily.

The findings indicated that the emissions of CH_4 , N_2O , and NH_3 from manure treated with waste from the lemon juice business were measured at 13, 0.219, and $2.523 \text{ g m}^{-2} \text{ day}^{-1}$, respectively. The emissions of CH_4 , N_2O , and NH_3 from manure

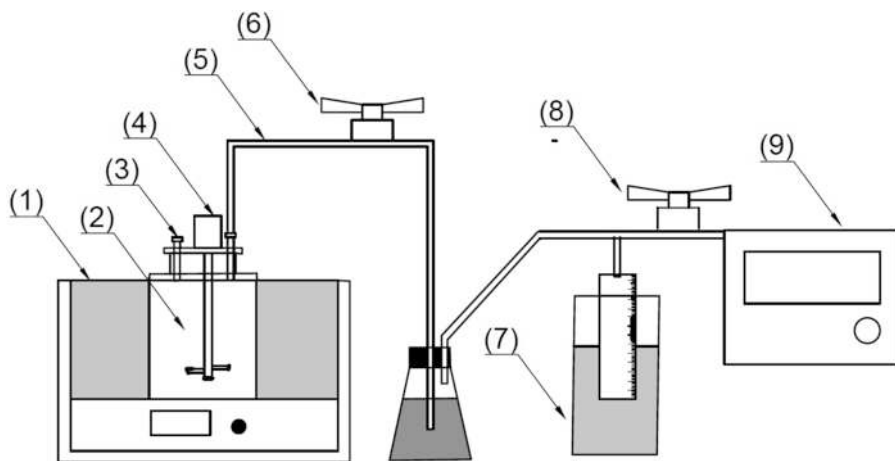


Figure 8.1 Main components of the treatment system, where (1) thermostatic water bath, (2) bioreactor, (3) material inlet, (4) motor of the mixer, (5) gas tube, (6) water trap, (7) gas volume measurement, (8) valve, and (9) gas analyzer.

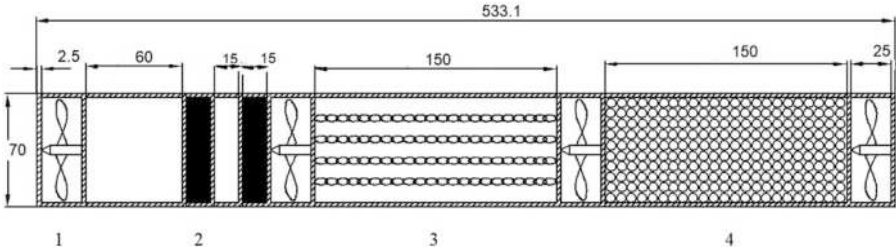


Figure 8.2 Design of the biological chemical filter, where (1) exhaust fan, (2) sponge, (3) metal chains, and (4) plastic biocarriers (all values are in centimeters).

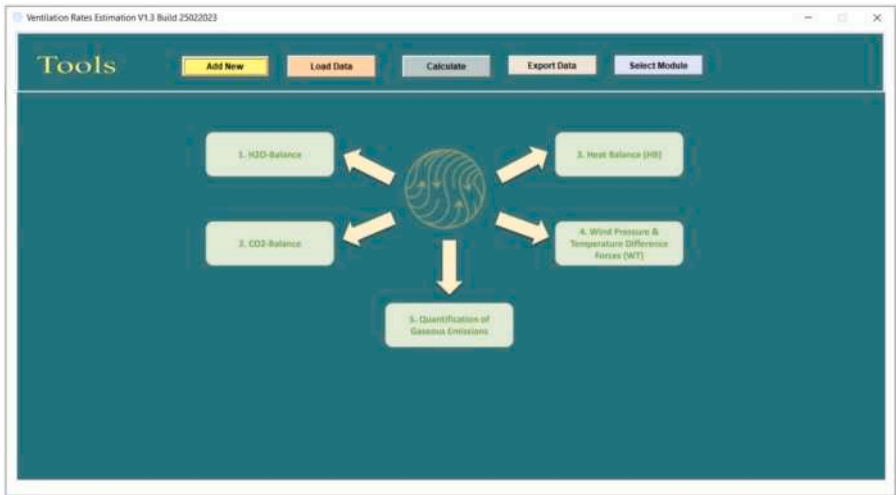


Figure 8.3 Architecture and modules of the software.

treated with waste from the orange juice business were measured at rates of 13.58, 0.223, and 2.581 g m⁻² day⁻¹, respectively. The gas emissions from the control sample, which consisted of a combination of manure and water, were measured at rates of 58.21, 0.347, and 18.9 g m⁻² day⁻¹ for CH₄, N₂O, and NH₃, respectively. The study revealed that the application of lemon juice production waste to manure yielded the most efficient treatment results compared to other methods investigated. Compared to the control, the decreased rates of ecologically damaging gaseous emissions from animal manure are increased by 348% for CH₄, 58% for N₂O, and 649% for NH₃.

Based on the above, the most important findings of the method of reducing emissions of gases harmful to the environment (GHGs and NH₃) from livestock manure by adding biological waste from agricultural industries with this invention are

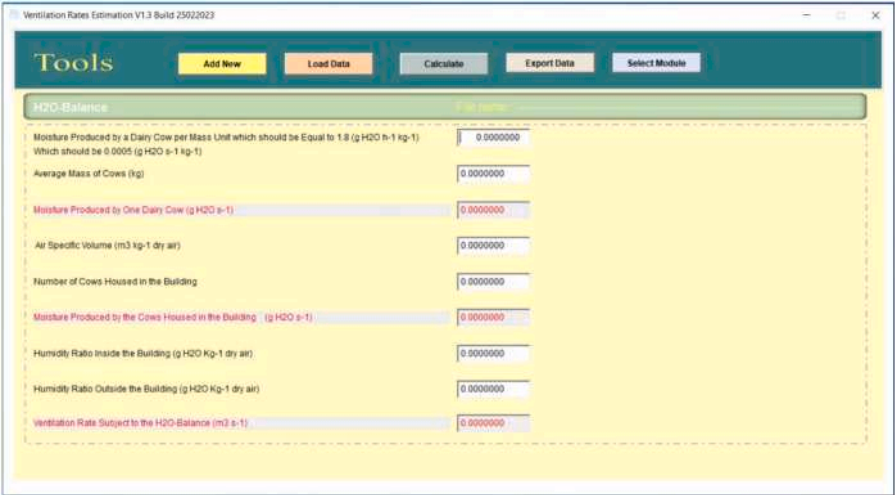


Figure 8.4 Screen of entered and calculated values of H₂O-balance.

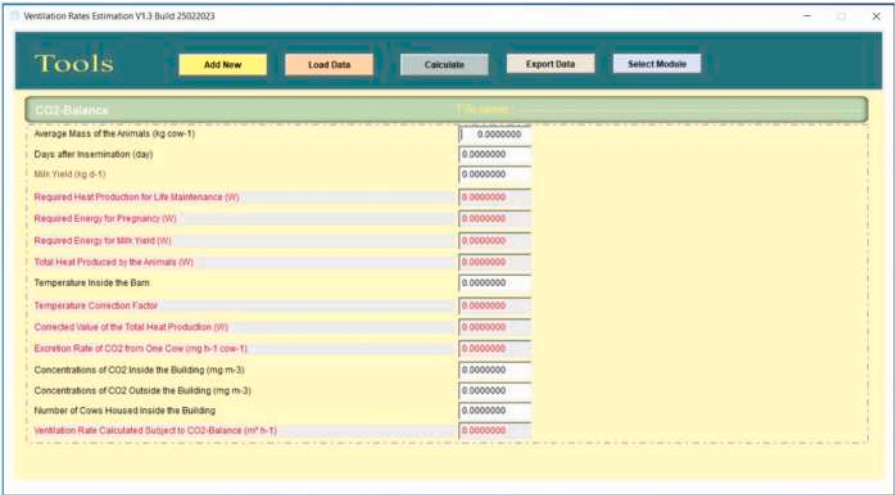


Figure 8.5 Screen of entered and calculated values of CO₂-balance.

the success of adding acidic biological waste from agricultural industries (whey and waste from making lemon and orange juices) to livestock manure, which raises the acidity of the manure by reducing the pH value, which leads to the inhibition of bacteria present in the manure that break down organic materials, resulting in the

Heat Balance (HB)		Heat Balance	
Average Mass of the Animals (kg cow-1)	0.0000000	Perimeter Length of the Building (m)	0.0000000
Days after insemination (day)	0.0000000	Air Density (kg m-3)	0.0000000
Milk Yield (kg d-1)	0.0000000	Air Temperature inside the Barn (°C)	0.0000000
Required Heat Production for Life Maintenance (W)	0.0000000	Air Temperature Outside the Barn (°C)	0.0000000
Required Energy for Pregnancy (W)	0.0000000	Ventilation Rate Subject to the Heat Balance (m3 h-1)	0.0000000
Required Energy for Milk Yield (W)	0.0000000		
Total Heat Produced by the Animals (W)	0.0000000		
Overall Heat Transfer Coefficient of the Building Component 1 (W m2 °C)	0.0000000		
Overall Heat Transfer Coefficient of the Building Component 2 (W m2 °C)	0.0000000		
Overall Heat Transfer Coefficient of the Building Component 3 (W m2 °C)	0.0000000		
Overall Heat Transfer Coefficient of the Building Component 4 (W m2 °C)	0.0000000		
Area of Building Component 1 (m2)	0.0000000		
Area of Building Component 2 (m2)	0.0000000		
Area of Building Component 3 (m2)	0.0000000		
Area of Building Component 4 (m2)	0.0000000		

Figure 8.6 Screen of entered and calculated values of heat balance.

emission of these gases. Thus, raising the acidity of livestock manure reduces emissions of GHGs: CH_4 and N_2O ; as well as harmful gas: NH_3 .

In practice, the acidic biological waste from agricultural industries (whey and waste from making lemon and orange juices) to livestock manure, which is usually stored in underground pits inside livestock buildings, which results in reducing the indoor gaseous concentrations, that is, the gaseous concentrations in the air inside the livestock buildings, which ultimately leads to decrease the gas emissions from livestock buildings.

8.4.2 Exhaust air treatment

The current invention reduces livestock facility gas, odor, and dust emissions with a BCF. Briefly, the process is: (1) A novel four-phase BCF prototype has been created. The first step is a de-duster that collects PM_{10} , $\text{PM}_{2.5}$, and PM_{10} dust. The second phase is a desulfurization unit with chains that grow H_2S -scavenging bacteria. This unit converts H_2S to harmless sulfa and water. To generate energy, *Nitrosomonas* bacteria capture NH_3 and N_2O in the third phase. Nitrite is a byproduct. Nitrobacteria convert nitrite to nitrate. After this phase, sodium sequesters the nitrate to produce sodium nitrate, a food preservative. (2) Nanoparticles were synthesized to target bacterial colonies by replacing the co-enzyme heavy metal. Bacteria activity increased after this intervention. (3) Laser radiation was used to divide bacterial colonies, increasing their cell count. The results demonstrated that in a standard 150-cow dairy barn, the suggested BCF reduced emissions from 4,059,194 to 170,820 kg CO_2 equivalent year. Thus, 3888374 kg of CO_2 equivalent can be saved. This technology reduces dairy barn gaseous emissions by 196% compared to the standard

method. CO₂ and total GHGs, which contribute to global warming, are reduced (Samer et al., 2021b).

This invention relates to an apparatus and method for reducing emissions of NH₃, H₂S, N₂O, CH₄, CO₂, dust, VOCs, and odors from animal production buildings. The device and method are based on: (1) Manufacturing and implementing a chemical biological filter, and it consists of four stages: The first stage is a device for removing PM₅, PM₁₀, and PM₂₀ dust; The second stage is a sulfur removal unit consisting of chains in which bacterial colonies are cultured to remove H₂S, where this unit captures H₂S and decomposes it into the water and harmless sulfate; in the third stage, *Nitrosomonas* bacteria use NH₃ and N₂O as energy and release nitrite, which Nitrobacteria converts into nitrate, which is then removed by sodium to create sodium nitrate, a food preservative. (2) Nanoparticles were prepared and used to treat bacterial colonies by replacing the heavy metal in the coenzyme structure, increasing bacterial activity. (3) Lasers-induced cell division in bacterial colonies. Thus, the number of bacterial cells increased. The method and the device can be summarized and described as follows (Samer, Loebisin, et al., 2011):

1. Manufacturing and implementing the first stage, which is a dust removal device consisting of a cylinder with two stages of purifying the air from dust using sponge pads, with the thickness of each pad being 15 cm (Fig. 8.2).
2. Manufacturing and implementing the second stage, which is a cylinder containing metal chains.
3. Manufacturing the third stage, which is a cylinder containing a medium of plastic balls carrying bacteria, that is, plastic biocarriers, with rough surfaces with a diameter of 2 mm (Fig. 8.2).

Wind Pressure & Temperature Difference Forces (WT)	
Angle between the Wind Direction and the Main Axis of the Building	0.0000000
Ratio of the Area of the Openings in the Long Side of the Buildings to the Whole Area of the Side	0.0000000
Effectiveness of Air inlets	0.0000000
Wind Velocity Outside the Barn (m s ⁻¹)	0.0000000
Free Inlet Area (m ²)	0.0000000
Ventilation Rate Due to Wind Pressure (m ³ s ⁻¹)	0.0000000
Height Difference between the Inlet and the Outlet (m)	0.0000000
Acceleration of the Gravity (m s ⁻²)	0.0000000
Temperature Inside the barn (K)	0.0000000
Reduction Factor which is usually Considered 0.65 for Agricultural Buildings	0.0000000
Temperature Outside the barn (K)	0.0000000
Discharge Velocity Due to Temperature Difference Forces (m s ⁻¹)	0.0000000
Ventilation Rate Due to Temperature Difference Forces (m ³ s ⁻¹)	0.0000000
Ventilation Rate based on the Combined Wind Pressure and Temperature Difference Effects (m ³ s ⁻¹)	0.0000000

Figure 8.7 Screen of entered and calculated values of the method of the wind pressure and temperature difference forces.

Quantification of Gaseous Emissions	
Ventilation Rate (m ³ h ⁻¹)	0.0000000
Concentration of the Gas under Consideration (g m ⁻³)	0.0000000
Mass Flow Emission Rate of the Gas under Consideration (g h ⁻¹)	0.0000000
Number of Cows Housed Inside the Building	0.0000000
Specific Gas Emission Mass Flow Rate per Cow (g h ⁻¹ cow ⁻¹)	0.0000000
Average Mass of the Cows Accommodated in the Building (g)	0.0000000
Gas Specific Mass Flow Emission Rate per Animal Unit (g h ⁻¹ AU ⁻¹)	0.0000000
Emission Factor (kg yr ⁻¹ AU ⁻¹)	0.0000000

Figure 8.8 Screen of entered and calculated values of gas emissions.

4. The bacteria were pretreated by being exposed to a laser source with a wavelength of 532 nanometers for 2 hours, and nickel nanoparticles were added to the bacteria, then they are added to the plastic biocarriers, then they were filled in the designated stage.
5. Installing four exhaust fans at the inlet and outlet of the filter and between the different stages.

A practical experiment was conducted to achieve this by manufacturing and implementing a chemical biological filter to study its ability to absorb and retain NH₃, H₂S, N₂O, CH₄, CO₂, dust, and VOCs, and odors from animal production buildings compared to the traditional biofilter. Gas concentrations were measured using an infrared photoacoustic analyzer (gas meter) every 5 minutes before and after the filter and repeated with and without laser exposure and the addition of nanoparticles. In the same manner, dust quantities were estimated using the quantification method. The results showed that the filter could reduce emissions from 4,059,194 to 170,820 kg CO₂ equivalent per year from a typical 150-head dairy cow barn. Thus, the equivalent of 3,888,374 kg CO₂ equivalent can be saved. Through this method, it is possible to achieve high reduction rates of harmful gas emissions from dairy cow barns by 196% compared to the traditional method.

Based on the above, the most important findings of a method and device for reducing gas, odor, and dust emissions from animal production buildings with this invention are:

1. The success of manufacturing, implementing, and using the device to reduce gas, odor, and dust emissions from animal production buildings.
2. The device succeeded in removing NH₃, H₂S, N₂O, CH₄, CO₂, dust, and VOCs that cause odors, as well as trapping dust.

3. The success of spherical nickel nanoparticles, whose diameter ranges from 7 to 28 nm, in increasing the efficiency of the chemical biological filter.
4. The success of photobiostimulation using a 532 nm laser with the addition of nickel nanoparticles succeeded not only in reducing the period of bacterial adaptation but also in reducing the time to achieve the highest filter performance.

8.5 Application

8.5.1 Manure treatment

This technique can be implemented in the field of environmental protection by reducing emissions of harmful gases to the environment (GHGs and NH_3) from livestock manure and exploiting biological waste from agricultural industries (food factories) with the aim of treating animal waste in all animal production farms such as dairy cow farms and fattening calf farms.

8.5.2 Exhaust air treatment

This technology can be exploited in the field of environmental protection by reducing harmful emissions to the environment, NH_3 , H_2S , N_2O , CH_4 , CO_2 , dust, VOCs, and odors from production buildings. Livestock farms, including related animal production facilities, such as dairy cow farms, fattening calf farms, and poultry farms.

8.6 Software for quantifying greenhouse gases and NH_3 emissions from livestock barns

In order to quantify the GHGs and NH_3 emissions from naturally ventilated dairy barns, several calculations and procedures should be accomplished; this necessitates time and effort, with the probability of making mistakes. This section presents a tool to support users, engineers, and specialists in performing these computations using a software program that can be installed on laptops and personal computers to save time and effort. The applied methodology for configuring the desktop software program was based on literature (Samer, 2010; Samer et al., 2012b), where a mathematical model was developed for each module to perform the calculations based on equations gathered from literature (Samer et al., 2011a, 2011b). Afterwards, a flowchart was created, and the mathematical model was integrated into the flowchart (Samer et al., 2013; Samer, Müller, et al., 2011). Subsequently, Microsoft Visual FoxPro 9.0 Service Pack 2.0 was used to develop the software program by combining the flowchart and the mathematical model and creating the user interface (Samer et al., 2019). Data came from dairy farms, government agencies, NGOs, and literature. The acquired data were used to calculate using the conventional method and compared to the software results (Samer et al., 2022, 2023a, 2023b). Both conventional and digital (software) methods yielded identical results. The software (Figs. 9.3, 9.4, 9.5, 9.6, 9.7 and 9.8) calculates GHG and NH_3 emissions from naturally ventilated dairy barns.

8.7 Summary and conclusions

The GHGs and NH_3 emissions from livestock farms mainly originated from manure storage tanks outside the buildings as well as the manure stored in underground pits inside the housing barns. Therefore, the emissions reduction technologies should focus on (1) reducing the emissions from manure stored in outside tanks and (2) reducing emissions from livestock barns. This chapter describes two emissions reduction technologies that fulfill both requirements.

The initial experiment involved treating dairy manure with waste from the citrus juice business and measuring the emissions of CH_4 , N_2O , and NH_3 gases. The findings indicated that the gas emissions from manure treated with waste from the citrus juice business were $13 \text{ g m}^{-2} \text{ day}^{-1}$ for CH_4 , $0.219 \text{ g m}^{-2} \text{ day}^{-1}$ for N_2O , and $2.523 \text{ g m}^{-2} \text{ day}^{-1}$ for NH_3 . The gas fluxes released from the control sample, which consisted of a combination of manure and water, were measured at 58.21, 0.347, and $18.9 \text{ g m}^{-2} \text{ day}^{-1}$ for CH_4 , N_2O , and NH_3 , respectively. Showing a large reduction in gaseous emissions from manure. In the second one, a novel prototype of a BCF was manufactured; the developed filter consists of four phases/stages:

The initial stage involves a de-duster that captures dust particles of various sizes (PM_{10} , $\text{PM}_{2.5}$, and PM_{10}). The subsequent stage comprises a desulfurization unit, which includes chains where bacterial colonies of H_2S scavengers are cultivated. In the last stage, bacteria on plastic biocarriers are responsible for capturing NH_3 and N_2O . The findings showed a decrease in emissions from 4,059,194 to 170,820 kg of CO_2 equivalent per year in a standard dairy barn accommodating 150 cows. On the other hand, a desktop software program was presented that is able to compute the emissions of GHGs (CH_4 , NO_2 , NO , and CO_2), as well as NH_3 emissions from naturally ventilated dairy barns.

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Impact of climate change on plant productivity and ecosystem sustainability: challenges and solutions

9

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9.1 Introduction

Climate denotes the typical meteorological attributes over an extended duration for a particular area (Moazami et al., 2019). Climate change refers to alterations in the climate of a region due to both natural phenomena, such as volcanic eruptions, variations in solar radiation, ocean currents, and changes in the Earth's orbit, as well as anthropogenic factors, including the combustion of fossil fuels, deforestation, industrial agriculture, urbanization and modifications in land use (Prakash, 2024). Climate change is a complex worldwide concern, accelerated by both natural processes and human actions, impacting ecosystems, agricultural output, and biodiversity (Pope et al., 2022). One of the main causes of the unfavorable acceleration of climate change has been identified to be global warming and greenhouse gas emissions (Sovacool et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) predicts that the average global temperature will increase by 2°C by 2100 and 4.2°C by 2400 as a result of a continued rise in anthropogenic activities (IPCC, 2021). The temperature does not seem to rise over 2°C by 2100 at the existing level of radioactive force. But the risk is rising, mostly because the radioactive forces stabilize beyond 400 parts per million of CO₂ (Gbadeyan et al., 2024). Emissions of greenhouse gases, such as CO₂, CH₄, and N₂O, are the primary drivers of climate change, and the use of automobiles, farms, factories, and the burning of fossil fuels extremely increase the amount of these gases in the atmosphere (Gupta et al., 2022). According to a recent assessment by the International Energy Agency, global CO₂ emissions from energy usage spiked by 4.8% in 2021 following a slight decrease in 2020 as a result of the COVID-19 epidemic (Lee et al., 2023).

Earth is the main emphasis of climate change, which affects all facets of the natural world. Certain regions experience milder winters and enhanced plant stress due to rising temperatures driven by ecological changes. Climate change-induced warming is predicted to alter biophysical interactions in agriculture, impacting soil qualities, water requirements, species composition, growing seasons, and increased survival of insect pests (Ullah, 2017). Furthermore, variations in temperature and moisture content can have an indirect impact on the rate at which minerals and fertilizers are absorbed, which in turn can have an impact on agricultural output. The chemical characteristics of soil, including pH, soluble salt quantity and distribution, carbonates, nutrients, ability to exchange cations, and base saturation value, are additionally affected by extreme weather conditions (Nel et al., 2022). Increased precipitation and weathering rate cause rapid leaching, which in turn causes acidic soil. While toxic

heavy metals can pass more easily through soil with an acidic pH, the soil loses basic cations (Singh & Sharma, 2021; Singh et al., 2024). Climate change has significant implications for ecosystem stability and plant production, affecting critical growth conditions. Rising temperatures reduce crop resilience and yield by accelerating metabolic activities, increasing water loss, and exacerbating drought stress. These environmental changes also jeopardize food security and ecosystem sustainability by reducing biodiversity and disrupting processes like carbon sequestration and nutrient cycling (Scholes, 2016).

Asia, with 4.5 billion people, confronts severe climatic difficulties, particularly in rural regions, where 75% of the population lives and is most exposed to climate change consequences (An et al., 2022). One of the areas most at risk from climate change is Southeast Asia, which consists of several island nations. In addition to topographical challenges, people in the region are vulnerable because they largely depend on nature for their livelihoods (Lee et al., 2023). Therefore these nations deal with a variety of climate-related issues, including disruptions to livelihoods, food shortages, epidemics of diseases, and mass migration, which reinforces already-existing inequalities as well as poverty. Benitez-Alfonso et al. (2023) and Jain et al. (2015) studied a pathway to increase plant production, achieve sustainable agricultural intensification, and enhance climate resilience, also analyzing the mitigation and adaptation strategies implemented by various nations in response to climate change. Additionally, Alam and Rukhsana (2023) evaluated how agriculture, a vital economic sector, is significantly impacted by climate change, especially in terms of agricultural production and lives in both industrialized and developing nations. Confronting these challenges requires inventive and resilient strategies. To counteract how climate change affects agriculture output, solutions are to be found in the development of breeding and genetically modified crops that can withstand or thrive under changing weather conditions, sustainable practices for managing agriculture particularly crop selection, water conservation, and land use as well as ecosystem-based management of natural resources. This chapter represents the relationship between climate change, plant production, and ecosystem sustainability and also highlights the numerous challenges faced by natural and agricultural systems developing in stressful environments due to global warming.

9.2 Climate change: key drivers

Climate change can be brought on by both natural and man-made forces. The primary causes of this issue are changes in land use, industrial operations, deforestation, and greenhouse gas emissions, which raise sea levels, produce extreme weather, reduce biodiversity, and alter ecosystems visibly. Developing successful adaptation and mitigation approaches that will protect the sustainability of ecosystems requires an understanding of the causes and trends of climate change. Variations in important abiotic factors such as temperature, solar radiation, precipitation, and CO₂ levels are predicted to cause major variations in crop yield over the next few decades (Abbass et al., 2022). Major natural and anthropogenic drivers are given below:

9.2.1 Natural drivers

9.2.1.1 Solar irradiation variability

The Earth's climate system primarily receives its energy from the sun and variations in solar activity have historically driven natural climate changes. The amount of solar energy reaching Earth fluctuates due to the 11-year solar cycle, characterized by changes in sunspot activity. Periods of heightened solar activity, marked by increased sunspots, are linked to warmer temperatures, while reduced activity, such as during the Maunder Minimum (1645–1715), has been associated with cooler periods like the Little Ice Age. Although solar variability contributes to short-term climate fluctuations, human activities play a far more significant role in driving current global warming (Fahey et al., 2017).

9.2.1.2 Volcanic eruptions

Volcanic eruptions, though relatively minor events, can cause significant climate changes. Active volcanoes release large quantities of sulfur dioxide (SO_2) into the atmosphere, which oxidizes to form sulfuric acid (H_2SO_4). This process increases Earth's albedo and induces negative radiative forcing (RF). Additionally, volcanic eruptions contribute to ozone (O_3) depletion and alter atmospheric heating and circulation patterns. These eruptions also emit CO_2 and water vapor, impacting the climate of nearby regions. Volcanic activity has been linked to the initiation of El Niño events through volcanic RF. For instance, the Mount Pinatubo eruption led to a global temperature decrease of 0.5°C (Cole-Dai, 2010).

9.2.1.3 Biosphere and land use

Vegetation and ecosystems play a key role in controlling atmospheric CO_2 levels through processes like photosynthesis and respiration. Natural disturbances, such as wildfires or pest infestations, can change forest cover, thereby affecting carbon storage and influencing the climate. Moreover, variations in vegetation patterns driven by climate fluctuations can alter regional albedo and disrupt hydrological cycles.

9.2.2 Anthropogenic drivers

9.2.2.1 Emissions of greenhouse gases and global warming

The main cause of climate change has been a steady rise in greenhouse gas emissions brought on by human activity. Methane (16%), carbon dioxide (76%), and, to a lesser extent, nitrous oxide (2%), are the main greenhouse gases. Because some of the sunlight that strikes the earth is rereflected into space, and the rest is converted to heat that keeps the earth and atmosphere warm enough for life forms to survive, the temperature of the atmosphere was kept within a reasonable range until recently (Mukherjee et al., 2024). The build-up of greenhouse gases and water vapor creates a transparent layer in the atmosphere that reradiates and absorbs net heat energy, or infrared radiation, emitted from the Earth's surface, causing the temperature to rise

(Jain et al., 2015). Nitrous oxide traps heat 300 times more effectively than CO₂ and methane 25 times more effectively. Up to 2019, 61% of global emissions came from the United States, United Kingdom, EU, Canada, Australia, Japan, and Russia, which were the top producers of CO₂. China currently produces the most CO₂ (27%), followed by the United States (11%), and India (6.6%); yet, India ranks ninth in terms of CO₂ production per capita. The primary cause of greenhouse gas emissions is the combustion of fossil fuels for industry and transportation, which releases carbon dioxide both during extraction and consumption. Before the Industrial Revolution, the atmospheric concentration of CO₂ was approximately 280 parts per million; today, it is 412 parts per million. The temperature of the ocean rises in tandem with the temperature of the atmosphere. About 25% of the carbon dioxide released by human activity is removed by the oceans, which also play a significant role in the global carbon cycle. Additionally, some CO₂ dissolves in ocean water, releasing carbonic acid, which makes the water more acidic. Increasing ocean temperatures and acidification diminish the oceans' ability to function as carbon sinks while also disrupting marine ecosystems and the communities that depend on them (Shivanna, 2022).

9.2.2.2 Ozone

Ozone, a naturally occurring greenhouse gas, is found in both the troposphere and stratosphere, where its levels are influenced by various anthropogenic and natural emissions. The production, destruction, and transport of ozone result in significant spatial and temporal variability, making RF calculations complex. In the troposphere, methane, nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (VOCs) act as precursors, leading to the photochemical formation of ozone both locally and far from the emission sources, contributing to positive RF on regional and global scales (Dentener et al., 2005). In the stratosphere, ozone is chemically broken down in reactions involving halogens such as chlorine and bromine, which are released through the decomposition of halocarbons originating from natural and human activities. This ozone depletion, particularly prominent in polar regions, results in a net negative RF (Myhre et al., 2014).

9.2.2.3 Aerosols

Aerosols are tiny particles suspended in the atmosphere, extending from Earth's surface to the edge of space. These particles consist of solid or liquid substances dispersed in a gas (Hidy, 2003). Primary aerosols, such as smoke, particulate air pollutants, dust, soot, and sea salt, primarily originate from human activities. Open burning is a significant contributor to atmospheric aerosols (Kumar et al., 2022). Dust, fog or mist, geyser steam, and forest exudates are examples of natural sources of aerosols. Aerosols influence climate change through two interactions: (i) aerosol-radiation interactions (direct effect) and (ii) aerosol-cloud interactions or cloud albedo effects (indirect effect). These interactions usually result in negative RF, but

the effect varies depending on the aerosol type. For example, by absorbing light, black carbon warms the atmosphere and produces positive radiofrequency (Flanner et al., 2009).

9.2.2.4 Contrails

When jet-powered aircraft are operating in the high-humidity mid-to-upper troposphere, they create a unique kind of cirrus cloud known as line-shaped (linear) contrails. Persistent contrails are produced when the surrounding air is supersaturated with humidity, which can last for several hours. Following development, persistent contrails lose their linear characteristics as they disperse and drift with the local winds, resulting in extra cloudiness in the cirrus that is identical to the background cloudiness. Other types of cirrus cloudiness, such as contrails and contrail cirrus, combine with thermal and solar radiation to produce a global net positive RF, making them obvious signs of human activity contributing to climate change (Burkhardt & Kärcher, 2011).

9.3 Effects of climate change on plant productivity

Climate change causes abiotic stress, which impacts numerous aspects of plants' morphology, anatomy, physiology, and biochemistry. Environmental stress is the main cause of the restricted production of most fruits and vegetables worldwide. Environmental stressors that affect crop productivity include high temperatures, salt, drought, pests, and disease incidence as shown in Fig. 9.1.

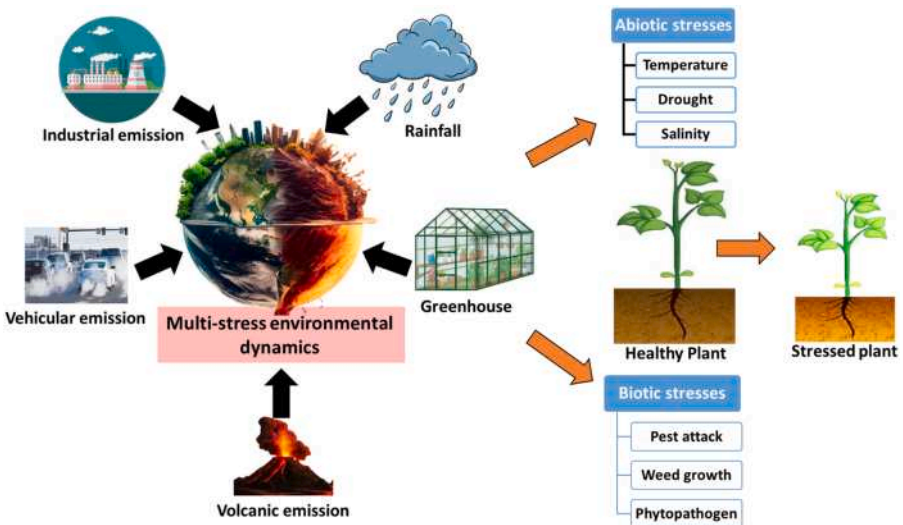


Figure 9.1 The impacts of climate change on environmental stresses, leading to challenges in plant growth and development.

9.3.1 Temperature

Extended exposure to high temperatures affects various structural and functional aspects of plants, influencing factors such as fruit formation, fruit dimensions, fruit mass, fruit qualities, pollens fertility, plant growth, flower drop, and reproductive fertilization (Fernández, 2023). Temperature directly influences numerous crop species, including cucurbits, lettuce, carrots, mustard, tomatoes, peppers, apples, peaches, and avocados, especially in low-humidity environments, resulting in a decline in the variety of pollinating insect species (Lal et al., 2023). Pollen germination in tomatoes and red peppers is negatively impacted at temperatures exceeding 27°C (Hwang et al., 2020). Additionally, studies have indicated that capsicum plants undergo blossom drop when temperatures rise above 30°C (An et al., 2022). *Pisum sativum* L. plants show a decrease in flower production, pod setting, and total yield when exposed to temperatures above 25.6°C during the crucial phases of the development of the reproductive part (Lamichaney et al., 2021). In watermelons, high temperatures affect sexual differentiation, leading to an increase in male flowers (Guan et al., 2020). Additionally, elevated temperatures and rising carbon dioxide levels may contribute to the occurrence of brown fleck illness and influence the development of potato tubers. High temperatures outside the normal growing season tend to trigger celery and lettuce plants bolting (Reed et al., 2022). The physiochemical reaction adversely affects crop quality, resulting in poor head development and reduced overall productivity. The synthesis of anthocyanin, the pigment that colors apples, is inhibited by an excess temperature (Karagiannis et al., 2020).

9.3.2 Salinity

Over the past 30 years, the prolonged impacts of rising temperatures and decreased rainfall have been positively linked to enhanced salinity of the soil in arid places due to reduced salt removal. In coastal farmlands, salinity levels have grown from 1% to 33% over the last 25 years (Ullah et al., 2021). High salinity presents a considerable obstacle to plant growth and crop productivity across various areas burdened by excess salt levels (Farzana et al., 2023). Additionally, 831 million hectares of agricultural land are currently affected by salinity, and by 2050, 50% of farmland is projected to face salt stress (Ullah et al., 2021). The main risks linked to rising salinity in soil include variables like low rainfall, increased surface vaporization, weathering of natural rock, irrigated using saltwater, and inadequate practices for managing land (Shahid et al., 2020). Elevated salinity disrupts plant K^+/Na^+ balances and causes accumulation of Na^+ and Cl^- , negatively affecting plant growth and development. Soil salinity has been shown to affect seed germination in a variety of crops via mechanisms such as osmotic stress, decreased pressure of turgor, stunted development, dying, leaves drooping decreased process of photosynthesis altered process of respiration, injury to cells, death of tissue, and, eventually, plant death (Ahmad et al., 2023). Eggplants, tomatoes, cucumbers, beets, peppers as well, and beet greens are somewhat sensitive to salty soils, whilst onions and Kagzi lime are more susceptible (Saqib et al., 2022). Changes in the climate, which is characterized by high radiation from the sun, saltiness, and a shortage of water, exacerbated

drought conditions in farming regions. Every kind of stress has considerable negative effects on crop development and growth (Ma et al., 2020).

9.3.3 Drought

The climate changes significantly affect the availability of water resources, resulting in a marked decrease in agricultural output due to intense drought conditions (Morales Alfaro et al., 2023). The combined effects of rising temperatures and falling precipitation can result in plants that are water-deficient because they reduce the amount of irrigation water available and increase evapotranspiration (Shah et al., 2024). Increased soil moisture from flooding disrupts water's osmotic movement outside of plant tissues. The composition of the soil and the environment affect biogeochemical mechanisms in soils, resulting in prolonged drought stress (Kühnhammer et al., 2023). As a result, the number of substances inside cells of plants increases, lowering the potential of water and disrupting the function of membranes and cellular functions such as photosynthetic in tomatoes (Pereira et al., 2023). The stress of water leads to multiple harmful effects on plants. These repercussions include changes in leaf orientation, where leaves become narrower, reduced seed germination rates, delayed maturation of crops, decreased and postponed flowering, a reduction in content of chlorophyll, a diminished rate of transpiration, hindered absorption of nutrients, and a substantial drop in overall productivity. Such adverse impacts can significantly hinder agricultural productivity and crop quality (Mahmood et al., 2023).

9.3.4 Disease incidence and pests in horticulture crops

Diseases of crops are currently predicted to account for about 16% of the decline in worldwide agricultural output, posing a substantial threat to the security of food that may be exacerbated by changes in the climate (Saqib et al., 2022). Climate factors that influence the severity and distribution of plant diseases include changes in patterns of precipitation, an increase in temperatures, increased humidity levels, dry conditions, and elevated concentrations of carbon dioxide (CO₂) and ozone (O₃) (Baker et al., 2022). Fluctuations in gas levels might have a beneficial as well as detrimental impact on the occurrence and severity of various disorders. On the one hand, elevated carbon dioxide and ozone levels may reduce plant resistance expression, increase pathogen attacks, and encourage faster microbial evolution. Conversely, increased CO₂ has been observed to extend the latent periods of pathogens (the duration between infection and the production of spores) ultimately leading to a slower rate of disease outbreaks (Zainab et al., 2020). Nevertheless, further research is necessary to elucidate how high concentrations of CO₂ and O₃ influence the dynamics of plant disease epidemics, as the interactions between these gases and disease processes are intricate and limited understood (Mora et al., 2022). Both beneficial and detrimental impacts on plants are caused by greenhouse gas emissions and abiotic climatic factors. To provide a deeper understanding of how increased concentrations of CO₂ and O₃ influence the incidence of plant diseases, further investigation is essential (Munaweera et al., 2022). Additionally, factors such

as drought, elevated temperatures, sulfur dioxide (SO₂), ozone, salinity stress, and heightened levels of CO₂ have been identified as crucial elements impacting pest populations and microbial infestations in horticultural crops (Shah et al., 2024). These insights emphasize the intricate relationship between climatic variables and plant health, indicating the urgent need for ongoing research to develop effective strategies for managing crop health in an evolving climate.

9.4 Ecosystems and biodiversity under climate change

The variety of life on Earth, which includes anything from bacteria to entire ecosystems like forests and coral reefs, is known as biodiversity, often referred to as biological diversity (Mooney et al., 2009; Padhy et al., 2022). Due to climate change, there are significant dangers to biodiversity, including possible negative consequences on it. Climate change is affecting freshwater, terrestrial, and marine ecosystems as mentioned in Table 9.1. The loss of native species, a rise in diseases, and widespread plant and animal mortality have been the main causes of the majority of recent extinctions caused by climate change (Pfenning-Butterworth et al., 2024). Temperature fluctuation and precipitation variation are two important aspects of climatic variability that are expected to have a direct and considerable impact on India's biodiversity (Yadav et al., 2021). According to a 2007 study by the Intergovernmental Panel on Climatic Change (IPCC), a scientific consortium of the United Nations, climate change effects on biodiversity are expected to become more frequent and intense under extreme weather conditions like heat waves and storms as temperatures and CO₂ levels rise (Parry, 2007).

An IPCC assessment states that at the present rate of greenhouse gas emissions, 20%–30% of plant and animal species are “potentially to be at a higher risk of extinction” (Tekalign & Balakrishnan, 2016). The climate of a species has a significant role in determining its global spread. Thus, by changing the composition of the flora and fauna, especially the keystone species, climate change has disturbed the equilibrium of the entire ecosystem (Rani et al., 2020). Different ecosystems from little rivers to deep seas, and from high mountains to low-lying areas are impacted by climate change to varying degrees. Some species are at risk of going extinct, while others are endangered. Basic ecological processes can be affected by extinction (Körner, 2019). The US Global Change Research Program Report, 2017 (Gulev et al., 2021) states that during the previous 115 years (1901–2016), the annual average surface air temperature has increased globally by approximately 1.8°F (1.0°C). One of the main factors contributing to the loss of biodiversity is environmental change. Environmental changes have always played a major role in shaping patterns of biodiversity and will probably remain one of the primary drivers of these patterns in the future. Environmental changes are examined in terms of climate change or changes caused by rising populations, deforestation, and other natural resource depletion. Climate change has a major effect on ecosystems and biodiversity (Weiskopf et al., 2020). As climate change gets more intense, there will likely be detrimental repercussions on ecosystems. Extended global warming would negatively

Table 9.1 Impact of climate change on different ecosystems.

Ecosystems	Episode of climate change	Impact on ecosystem	References
Marine eco-systems	Ocean acidification	Reduced calcification in marine organisms like corals, affects reef structures and species	Guinotte and Fabry (2008)
	Coral bleaching	Increased sea temperatures lead to coral bleaching, reducing biodiversity in coral ecosystems	Ainsworth and Brown (2021)
	Fish migration	Warmer oceans cause fish species to migrate to cooler waters, affecting marine food webs	Ottersen et al. (2010)
	Loss of marine biodiversity	Species unable to adapt to warmer, more acidic oceans face extinction, reducing biodiversity	Worm and Lotze (2021)
Terrestrial eco-systems	Forest ecosystem shifts	Changing temperature and precipitation patterns alter forest composition and tree species ranges	HilleRisLambers et al. (2015)
	Increased wildfires	Warmer, drier conditions increase the frequency and intensity of wildfires, damaging ecosystems	Mansoor et al. (2022)
	Desertification	Prolonged droughts contribute to land degradation and expansion of deserts, reducing biodiversity	Abdi et al. (2013)
	Grassland degradation	Shifts in precipitation patterns threaten grassland ecosystems, leading to species loss	Joyce et al. (2016)
	Loss of habitat	Rapid climate shifts force species to migrate or adapt, leading to habitat fragmentation	Leimu et al. (2010)
Mountain eco-systems	Glacier melting	Warming temperatures cause glaciers to melt, impacting species dependent on cold environments	Sommaruga (2015)
	Species migration	Species are forced to migrate to higher altitudes, altering the ecosystem balance	Aitken et al. (2008)
	Alpine habitat loss	As temperatures rise, alpine species lose their habitats, leading to reduced biodiversity	Grabherr et al. (2010)
Freshwater eco-systems	Altered water temperature	Increased temperatures in freshwater bodies affect aquatic species and water quality	Whitehead et al. (2009)
	Increased flooding	Changes in rainfall patterns lead to more frequent and intense flooding, disrupting freshwater habitats	Siddha and Sahu (2022)

impact numerous ecosystems and the services they offer, often leading to irrevocable consequences that impact society, customs, and the economy. Climate change creates hazards to biodiversity that can be assessed using currently available vulnerability and effect assessment criteria (Sintayehu, 2018).

9.4.1 *Climate change affects marine ecosystems*

By absorbing, storing, redistributing, and releasing heat, the ocean plays a crucial role in controlling Earth's energy balance and limiting variations in the planet's surface temperature (Emanuel & Sobel, 2013). The physicochemical characteristics of the marine environment are altered by global climate change in several ways, including increases in sea surface temperature, ocean acidification, and oxygen depletion. The distribution, abundance, growth, development, neurosensory abilities, and survival of marine biodiversity may all be negatively impacted by these changes. Increased frequency and intensity of extreme weather occurrences worsen the impacts. Recent increases in global temperature have raised concerns about the potentially catastrophic consequences for biodiversity. An increase in the quantity of greenhouse gases produced by human activity and released into the atmosphere is causing the surface of the earth to heat. Totally, 90% of the extra heat has been absorbed by the ocean, resulting in an average 0.63°C rise in sea surface temperature globally over the last century (Dervash et al., 2023). A warmer sea surface decreases gas exchange efficiency, which lowers oxygen dissolution and, hence, dissolved oxygen concentrations (Verberk et al., 2020). It is anticipated that this may worsen the occurrence of marine dead zones, which are typified by hypoxic seawater and are frequently exacerbated by the influx of nutrients from human sources that deplete oxygen. There have been reports of marine dead zones close to the shores of China, Japan, South America, and New Zealand. Marine dead zones are linked to places with high human activity (Marques, 2020).

Climate change causes extreme climate on the ocean, which can harm coastal ecosystems to varying degrees. It also causes changes in the strength and frequency of storms and waves (Babcock et al., 2019). Although the effect was confined, seaweed canopies have been reported damaged. The degree of damage was correlated with wave energy, suggesting that it impacted the ecosystems' structural integrity, productivity, and local variety (Ummenhofer & Meehl, 2017). According to a study, storms altered the spatial and environmental effects on macrobenthic assemblages (Corte et al., 2018). This suggests that the frequency of extreme weather events, especially storms, will shift, resulting in changes to the environmental and geographical factors that determine macrobenthic populations. When organisms are faced with sudden changes and little time for adaptation, the survival of those creatures is threatened by an increase in the frequency of catastrophic climate events. This is supported by ecosystem models implying widespread mortality of habitat-forming taxa, which is produced by more frequent and severe impacts of extreme climate events, could have long-term and irreversible consequences (Babcock et al., 2019).

9.4.2 Ocean warming

An increase in temperature, when combined with other stresses, changes the resilience and prevalence of infections, resulting in disease outbreaks that impact the biodiversity of marine ecosystems. Outbreaks caused a significant reduction in kelps in New Zealand (*Ecklonia radiata*) and Japan (*Laminaria religiosa*) (Burge et al., 2014). Changing ocean temperatures have an impact on the distribution of lower trophic-level marine organisms, but they also have an impact on predator abundance. A study found that the decrease in zooplankton in the Norwegian Sea as a result of ocean warming led to an increase in pelagic planktivorous fish, including Atlantic mackerel (*Scomber scombrus*) and blue whiting (*Micromesistius poutassou*). These fish were likely to support the populations of toothed whales, long-finned pilot whales, and killer whales (Nøttestad et al., 2015). In light of the warming ocean and changing trophodynamics, this also suggests the ecological adaptability of marine creatures. While the rising sea surface temperature favored lower-latitude dwelling short-beaked common dolphins (*Dephinus delphis*) and striped dolphins (*Stenella coeruleoalba*), species distribution models agreed with the changing abundance of species and showed a decline of higher-latitude dwelling Atlantic white-sided dolphins (*Lagenorhynchus acutus*) and white-beaked dolphins (*Lagenorhynchus albirostris*) (Hammond et al., 2017).

9.4.3 Ocean acidification

Ocean acidification primarily affects marine species in terms of their capacity to endure, calcify, develop, grow, and metabolize. When the pH of the water decreased, corals, mollusks, and echinoderms showed a decline in survival that did not appear to affect crustaceans (Kroeker et al., 2013). The degree to which marine species are sensitive to acidification varies depending on their life stage. Early in life, molluscs and sea urchins developed less, and their larvae were most vulnerable to acidification throughout the mollusc's life cycle. This may be connected to a notable decrease in molluscs larvae metabolism due to ocean acidification (Chambers et al., 2014).

9.4.4 Climate change affects terrestrial ecosystems

A wide range of terrestrial ecosystems, including wetlands, lakes, crops, forests, grasslands, and deserts are significantly impacted by climate change, which is now a confirmed fact due to the increasing amount of greenhouse gases in the atmosphere. Recent years have seen a significant rise in the amount of research conducted to improve our knowledge of the spatiotemporal variation in climate parameters, including radiation, temperature, and precipitation, as well as the impacts of these variations on terrestrial ecosystems (Piao et al., 2019). Ecosystems in the north are already being significantly impacted by climate change, with consequences for living things, infrastructure, and the state of the economy. It is happening in combination with other human-made causes like altered land use and air pollution. Climate change has the potential to have catastrophic effects on human society, economics, and natural terrestrial and other ecosystems. Potential repercussions include shifting

regional weather patterns, sea level rise, and ice melting at higher latitudes and elevations. Several natural disturbances, including increased desertification, extreme droughts, floods, tropical cyclones, more frequent wildfires, rising sea levels, and melting glaciers, are brought on by an increase in the atmospheric abundance of greenhouse gases, which also modifies the energy balance of the climate system of terrestrial ecosystems (Rangwala & Miller, 2012).

Land use changes, deforestation, and decreases in soil organic matter levels as a result of soil tillage have all contributed significantly to climate change. Large tracts of Asia and Europe have been cleared of forest throughout the past several millennia, usually to turn them into fields for agriculture. The main factor affecting the carbon cycle throughout the 18th and 19th centuries was the destruction of forests in the northern hemisphere, mostly in North America, for agricultural purposes (Beillouin et al., 2022). Increased global temperatures are already having an impact on the growth and behavior of numerous terrestrial ecosystem organisms. Crop yields may rise as a result of rising temperatures, provided they are not extreme. Nonetheless, higher temperatures may cause faster development and reduced crop yields in small grain cereal crops. Natural ecosystems and biodiversity have already been observed to be impacted by climate change. The loss of biodiversity brought on by climate change has altered the pattern and dynamics of material and energy circulation in terrestrial ecosystems (Dandotiya & Sharma, 2022).

9.5 Challenges in maintaining plant productivity and ecosystem sustainability

Plant productivity is greatly challenged by climate change across so many interconnected mechanisms:

9.5.1 *Temperature variability*

Temperature is one of the primary variables which influences plant diversity and abundance because of species-specific physiological limits (Parmesan et al., 2003). It not only establishes the geographic region where plants can grow successfully but also affects development stages, growth rate, and crop yields (Rehman et al., 2015). Every plant has a particular temperature demand for transit via various phenophases and throughout the life cycle (Luo, 2011). Extreme temperature fluctuations like very high and low temperatures mainly during responsive stages like flowering, can adversely impact the development, yield, and growth of plants. However high temperature is frequently associated with other environmental factors like wind conditions, water availability, and sunlight intensity. Higher temperature has the potential to raise atmospheric water demand, which may increase water stress by increasing water pressure deficits, which in turn reduces the yield and soil moisture. An additional effect of high temperatures include more frequent heat waves, and enhanced challenges by weeds, pests, and diseases which can further hamper crop production (Skendžić et al., 2021).

9.5.2 Land use and degradation

Land degradation not only affects the soil quality but also affects biodiversity, the ecosystem, and vital functions such as carbon sequestration, which contribute to raising food costs and forced migration (Lal, 2004). The UN has recognized land degradation as a global issue, that effect 25% of all land resulting causes up to \$230 billion loss in the annual economy (Nkonya et al., 2016). Agro-ecosystem affected by cropland degradation only causing losses of \$10.8 billion. This problem is becoming severe by climate change, which reduces crop production and soil fertility. Grain yield reduces by about 5% for each degree of temperature increase. Extreme climate condition like drought, irregular rainfall, high temperature, erosion, and soil sterility has negative agricultural impacts. In north India, the loss of groundwater make severe land degradation and desertification. Large bodies of water such as Lake Urmia mad Aral Sea have drastically diminished due to excessive removal and saline soil spreading due to moisture loss. Land degradation significantly impacts crop production and livestock production. Soil degradation is a major cause of land degradation, affecting several nations and covering around 1 billion hectares worldwide. Drought conditions are closely linked with it (Tewari & Arora et al., 2013). Major sources of salinization are associated with improper irrigation methods and unsuitable farming practices, where poor quality irrigation water and poor drainage systems make the problem severe and salt accumulation in soil (Arora et al., 2018).

9.5.3 Biodiversity and habitat loss

The reduction in biodiversity is an important issue that endangers the equilibrium of the ecosystem by decreasing both marine and terrestrial species diversity (Arora et al., 2018). World Wide Fund (WWF) reported that 52% of global diversity declined between 1970 and 2010. The loss of biodiversity has been accelerated over the last 40,000 years by anthropogenic activities, even if something happened naturally. The main reason for biodiversity loss is climate change, deforestation, pollution, and habitat fragmentation. Increasing worldwide temperature affects the distribution of species, with projections indicating up to 37% of terrestrial species may go to face extinction by 2050 (Tang et al., 2018). Sea covering approx. 72% of Earth's surface, which supports vital blue carbon habitats such as mangroves that reduce CO₂ emission yet human activity is gradually degrading the ecosystem (World Bank UNDESA, 2017). Marine ecosystems mainly coral reefs, face danger from pollution and warming, increasing danger of extinction for species across all taxa. Water and air pollution additionally affects ecosystem, endangered biodiversity, and microbial growth essential to soil health and nutrient cycling (Panizzon et al., 2015). For sustaining ecosystem and human life rapid action is required to save habitats and preserve biodiversity.

9.5.4 Water availability

Crop production is mainly dependent on water availability; more than 80% of world crop production depends on rainfall (Olesen et al., 2002). Climate change may have a sustainable impact on agriculture through changes in rainfall patterns, evaporation,

soil moisture, and runoff, changes in seasonal precipitation are more important than temperature fluctuation mainly in regions with dry seasons (Huntington, 2010). A dried trend is experienced in Northern and Southern Africa, sections of Latin America, Southern Europe, and Australia, forecast for the middle of the century suggested that up to 10% enhancement in drought and yearly moisture deficit may exceed 200 mm. Water and heat limitations already pose difficulties for Mediterranean cereal crops, consequently, drought-tolerant crops such as grapes, olives, and citrus are essential (Olesen and Bindi, 2002). Additionally, irrigation upgrades and moisture preserving techniques are extreme to sustain productivity under these shifting conditions. Heavy rainfall is impacting plant productivity, soil versatility, and quality in northern European and parts of America. The usual 2-year event increased by 7% between 1951 and 1999 (Min et al., 2011). While the specific path of climate change remains unknown, projections indicate that rising extreme water levels will cause major challenges to agriculture production in the coming year (Skendžić et al., 2021).

9.6 Case studies

9.6.1 *International case studies*

In California both regular and organic farms are successful; these types of farms are smaller and produce a great variety of crops. A key ecological practice utilized by farmers, mainly on organic farms is the creation of hedgerows, which are boundaries of native perennial vegetation planted around fields. Hedgerows are planted by many farmers because of their positive benefits on the ecology and economy also including increased biodiversity, better pollination services, and pest control (Schleich et al., 2019). It also improves appearance, provides security for bees and natural predators, assists wildlife, reduces soil erosion, increases carbon storage, serves as windbreaks, and assists in weed management (Garbach and Long, 2017). However, concern over hedgerows suffers including high installation expenses, potential of weed growth, and competition with crops for pollinators. This issue can discourage nonadopters, especially short-term renters who may not recognize immediate advantages. Research in California indicates the essential role of hedgerows in diversity, mainly for bird species and native bees, by increasing floral diversity and providing an environment for specialized organisms (Garibaldi et al., 2019). While hedgerows enhance pollination and pest management for some crops. Hedgerows in tomato fields reduce pesticide requirements by increasing the invertebrate predator population, however, their impact on pollination varies according to the crops (Ponisio et al., 2019). Long-term financial advantages, such as reduced pesticide expanse and enhanced crop production, may balance early costs over time, especially for farmers dedicated to agriculture sustainability. Therefore, hedgerows perform as an effective, sustainable agriculture practice, balancing crop yield with ecological stability and allowing multifunctional farming systems in California (Morandin et al., 2016).

In the Midwest, scientists and farmers are working together to introduce native prairie plants on agricultural farms, generating grassland strips that decrease soil

erosion and nutrient loss while improving biodiversity. Although this technique reduces 10%–20% of land from the agricultural field, it does not affect productivity on the remaining areas, creating a diversification rather than intensification technique. Prairie strips can reduce phosphorus loss (77%), runoff (37%), and sediment loss (95%) (Garibaldi et al., 2016). Also, nitrogen loss is decreased by 70% but not significantly. These strips also support increasing the number of bird species, support wildlife, increase three-time pollinators and natural predators, and increase insect biodiversity due to enhanced plant diversity. Although yield and loss of income are low, prairie strips improve pest management and pollination services, particularly in systems that depend on pollinating organisms such as wheat-legume rotations (Chaplin et al., 2013). Transforming less efficient agricultural land to prairie strips could equalize economic losses through lower costs of inputs, particularly during severe weather. Organized conversion may assist preserve farmer income and improving water quality under climate change (Brandes et al., 2018). Implementation of prairie strips could be promoted by regulation and benefits centered on water quality standards, collectively with improved interaction and education. In intensive farming landscapes, prairie strips offer significant agricultural sustainability and ecological preservation advantages, producing a multifunctional solution for farming and environmental concerns (Brandes et al., 2016).

9.6.2 National case studies

Advanced agricultural technologies have been adopted by countries all over the world to promote agribusiness and achieve food security for the increasing population, often overlooking the effect on the environment, sustainability, and human health, mainly in developing countries. India is a country that has rapidly transformed its agricultural industry through the implementation of Green Revolution methods. This case study examines the effects of traditional and advanced farming in ecosystems and human health in three Indian regions—a dryland area, a canal-irrigated area and an ancient region with an 800-year irrigation history. In the canal-irrigated area, extensive rice farming practices are heavily dependent on chemical inputs, which cause water pollution, soil degradation, and health risks due to increased mosquito population, which transmit disease like malaria. The other region which is a dryland region obtains limited rainfall, participates in traditional agricultural farming employing minimum pesticides, preserving soil quality and biodiversity while reducing health risks. In the meanwhile, the ancient irrigated region has move from organic to advanced practices due to market forces. This change has altered the landscape, decreased biodiversity and increased health concerns similar to those in the canal-irrigated area, through farmers reported lesser observed adverse effects. Overall, this study shows the contrasting impacts of intensive advance agriculture versus traditional practices. Although modern techniques increase yields, they also cause serious environment and human health risks. Sustainable agricultural development should promote methods like combined pest management and agroecology, which create a balanced between yield and ecological conservation. Supportive policies such as education on sustainable farming and the availability of eco-friendly methods

can improve environmental conservation and improve health outcomes. This case study shows the importance of an extensive strategy for agricultural growth that balances food security with sustainability (Sarkar et al., 2011).

This study investigates the socio-economic, ecological, and policy impact of land use diversity in the Garhwal region of the Indian Himalayas. The landscape consists forests, established and shifting agriculture (SAS), with distinct system. Forests are divided into reserve and community forests, which provide essential resources such as fodder and fuelwood. Established agriculture include four agroecosystems: Rainfed Agroforestry System, Homegarden System, Rainfed Crop System and Irrigated Crop System (ICS). HGS is the most profitable, while RCS and RAS maintain biodiversity with minimal inputs. The interlinked nature of agriculture and forest management is shown by the ICS, which enhances productivity but also raises the stress on forest for manure. SAS which involves extended periods of fallow, cultural practices and promotes ecological diversity but less and efficient. Invasive species and overuse of local resources put a burden on forest ecosystem. Socio-economic practices highlights community equality, yet growing agriculture creates pressure on forests, highlighting the need for coordinated guidelines. The study promotes a sustainable development approach which utilizes technological and institutional innovations to connect agriculture with forest conservation. Such guidelines can enhance agricultural productivity and preserve forest services, promoting sustainability and resilience in the area shifting climate (Singh et al., 2008).

9.7 Mitigation and adaptation strategies

In ecological terms, adaptation signifies changes in an organism's physiology, behavior, or traits that enhance its environmental fitness, typically associated with genetic evolution. Adaptation plays a major role in climate change action by assessing vulnerabilities and impacts, as well as informing the development of response strategies. By adopting diverse adaptation approaches, the risks and severity of climate change can be mitigated.

9.7.1 Sustainable approaches to soil conservation and improvement

Enhancing soil conservation strategies can decrease soil carbon emissions, leading to a reduction in greenhouse gas emissions. Promoting agricultural practices that support carbon neutrality, such as organic and sustainable farming, aims to enhance carbon storage in soil and decrease greenhouse gas emissions, and improve soil as well as ecosystem health (Li et al., 2022). China aims to attain carbon neutrality by 2060 and peak carbon emissions by 2030, with the broader objective of combating global warming (Yuan et al., 2024). Conservation practices provide benefits beyond erosion control, including increased carbon sequestration, better biological activity, improved soil aggregate stability, and enhanced overall soil quality (Eekhout & de Vente, 2022).

9.7.2 Sustainable fertilizer production: practical solutions and strategies

Conventional fertilizers are major contributors to greenhouse gas emissions and environmental pollution. Sustainable alternatives offer a lower carbon footprint by optimizing production methods and utilizing eco-friendly materials (Wu et al., 2024). For instance, bio-fertilizers and organic fertilizers recycle agricultural waste, enhancing resource use efficiency, decreasing fossil fuel dependence, reducing emissions, and increasing soil fertility (Avsar, 2024). Advancements in synthetic biology and microbial fertilizers improve nutrient efficiency, limit fertilizer runoff and water contamination, and improve soil health, thereby boosting plant growth (Wei et al., 2024). Sustainable fertilizer production strategies also include green chemical processes and smart fertilization systems. Green chemical techniques reduce fossil fuel use in manufacturing, leading to a lower environmental burden from chemical production (Ganesh et al., 2021). Intelligent fertilization maximizes efficiency by controlling application and release, minimizing unnecessary synthetic fertilizer application. These solutions not only promote crop production but also support sustainable agriculture and climate goals by reducing chemical fertilizer dependency and greenhouse gas emissions (Yuan et al., 2024).

9.7.3 Potential strategies for water recycling and reuse

Innovative approaches to water reuse and recycling offer critical solutions for reducing the detrimental effects of climate change on plant yields. By improving water management practices, these solutions reduce agricultural water demand, addressing the challenge of water scarcity driven by climate shifts. Different techniques like drip irrigation and rainwater harvesting systems increase water efficiency, limit water wastage, and provide crops with sufficient irrigation, even in drought-prone areas (Feng et al., 2024). Technologies for wastewater regeneration and treatment can change domestic and industrial wastewater into irrigation water, reducing the strain on freshwater resources while mitigating pollution from wastewater discharge (Wu et al., 2024). Through the application of different strategies of water reuse maintain soil moisture, boost soil fertility, and provide nutrients to crops, supporting growth while improving the health and resilience of agricultural ecosystems through pollution reduction (Leonel & Tonetti, 2021). Thus, adopting these water management technologies is an effective approach to achieving sustainable agriculture and overcoming climate change challenges.

9.7.4 Biochemical responses and the synthesis of antioxidants

Plants synthesize several organic compounds in response to abiotic stress (Boscaiu & Fita, 2020). In adverse conditions, plants adapt by modulating various metabolic pathways. Drought stress triggers osmotic modification in plants, helping them retain water by producing molecules like proline, glycine betaine, and various sugars and ions. Proline is the most prominent osmolyte, essential for osmotic regulation and signaling, synthesized in the cytosol and plastid, with degradation in the mitochondria

(Ashraf & Foolad, 2007). It plays different critical roles in plant cells, such as stabilizing membranes and proteins, regulating cellular redox balance, scavenging free radicals, and mitigating oxidative stress in response to abiotic stresses (Hoque et al., 2008). Carbohydrates, particularly sucrose, are photosynthetic products essential for plant growth and development. Under stress, carbohydrates act as osmoprotectants, assist in osmotic adaptation, neutralize excessive ROS generation, protect membrane and DNA integrity, and promote the stability of enzymes (Bowne et al., 2012). For example, Farshadfar et al. (2008) revealed that wheat genotypes accumulate more soluble sugars at grain filling compared to pre-anthesis under high temperature or drought conditions.

Plants possess several defense mechanisms to protect against damage from ROS molecules. The degree of ROS production and the effectiveness of antioxidant mechanisms in plant cells determine the degree of oxidative damage (Moller et al., 2007). The antioxidant system is the primary defense mechanism, combining enzymatic and non-enzymatic variables to impede the synthesis of ROS. Enzymatic defenses include SOD, CAT, POD, ascorbate peroxidase (APX), glutathione reductase (GR), monodehydroascorbate reductase (MDHAR), glutathione-S-transferase (GST) and glutathione peroxidase (GPX), that scavenge ROS rapidly. To keep the membranes of photosynthetic cells intact when under oxidative stress caused by abiotic stressors, nonenzymatic mechanisms such as alkaloids, carotenoids, glutathione (GSH), ascorbate (AsA), tocopherol, phenolic compounds and nonprotein amino acids are vital components. Feng et al. (2024) and Thackeray et al. (2022) reported that stress-tolerant wheat plants had enhanced SOD activity, which aids in scavenging H_2O_2 under heat stress conditions. Similarly, Ratnayaka et al. (2003) showed that increased GR and APX activities, protect against cellular disruption from ROS during the recovery from water stress.

9.7.5 Phytohormone synthesis for enhancing climate resilience

Phytohormones (PHs) are naturally occurring chemicals produced in minimal concentrations throughout various parts of plants. While their primary function is to promote plant growth and development, PHs are also essential for enabling plants to adapt to harsh conditions (Fahad et al., 2015). They can affect the physiological and biological processes of plants through either application from outside sources or endogenous production, particularly in response to abiotic stresses like elevated temperature. There are many key PHs including indole acetic acid (IAA), gibberellic acid (GA), indole-3-butyric acid (IBA), abscisic acid (ABA), cytokinins (CK), ethylene (ET), and salicylic acid (SA). IAA and IBA are prominent forms of natural auxin that regulate critical aspects of plant growth, including apical dominance, differentiation, expansion, and cell division (Asgher et al., 2015). As reported by Akbari et al. (2007), the application of exogenous IAA significantly improved the length, fresh weight, and dry weight of hypocotyls in 3 genotypes of wheat exposed to stressful condition.

GA is essential for several developmental processes, such as seed germination and the growth of leaves and stems, lateral root formation, and flowering (Ahmad, 2010).

Free radical-induced lipid peroxidation is also diminished by it. All flowering plants contain ABA, a PH that is known to inhibit development and function as a signaling molecule in response to stressors imposed by climate change. Keskin et al. (2010) revealed that ABA-treated wheat plants activated genes such as MAPK4-like, TIP1, and GLP1, which are essential for adapting to stress. Synthesis of ABA increases under stress conditions, helping plants manage water deficits and extreme temperatures (Sah et al., 2016). ET is identified as an important growth regulator in the face of various stressors. Previous research revealed that elevated ET biosynthesis in plant cells rises tolerance potency to abiotic stresses such as inconsistent temperatures and drought conditions (Khan, 2014). Moreover, Narayana et al. (1991) reported that when wheat leaves were under water stress, ET synthesis was significantly enhanced.

9.7.6 Genomic insights into plant adaptation to climate change

Identifying the genetic foundation of complex characteristics related to climate adaptation in wild populations has been made easier by the proliferation of omics technology, databases, and recently created genome editing tools, enabling more effective combat against the negative consequences of climate change and the development of climate-adaptive crops (Ogura et al., 2019; Zaidem et al., 2019). Among the various methods are transcriptomics, metabolomics, landscape genomics, genome-wide association studies (GWAS), quantitative trait locus (QTL) mapping, and others. Both GWAS and QTL mapping may be carried out inside the lab or in the field on populations exposed to climate change effects like drought stress or high temperatures. These studies will identify possible genes and genomic areas implicated in climate change responses (Raza et al., 2023).

The identification of candidate genes linked to complex trait variation has been significantly aided by the combination of systems biology and other “omics” technologies (Palit et al., 2020). Metabolomics, transcriptomics, and proteomics are particularly effective in this context, as they allow for the quantitative and dynamic evaluation of transcript, protein, and metabolite activities across time. Information derived from these approaches can directly assist in predicting candidate genes associated with critical QTLs and in correlating proteins, metabolites, and pathways with traits of interest. The selection of candidate genes implicated in plant adaptation to unfavorable climatic circumstances requires the integration of genomics, landscape genomics, and systems biology. Once suitable pathways or genes are identified and validated, contemporary biotechnological techniques, including plants that are climate resilient can be produced by using genome editing and pathway engineering (Anderson & Song, 2020).

9.7.7 Nanotechnology solutions for increasing plant resistance to climate change

Nanotechnology is emerging as a crucial field for improving the resilience of crop plants to various environmental stresses caused by climate change, ensuring productivity while addressing present-day food security issues and challenges within

the food system (Li et al., 2015). This technology can revolutionize production systems using tools that precisely assess soil fertility, moisture levels, and nutrient concentrations in plants, along with monitoring temperature and crop pest diseases (Hossain et al., 2020). Additionally, these nano-tools facilitate real-time evaluations of plant growth and supply crucial information for precision farming strategies. Titanium dioxide nanoparticles (nTiO₂) are recognized as an effective nutrient source that boosts biomass production in plants by enhancing nitrogen assimilation in cereal crops (Arumugam et al., 2002). Studies have revealed that the optimal application of nanotitanium dioxide increases growth in both the roots and shoots of cereal crops (Kashyap et al., 2020). Moreover, these nanoparticles (NPs) not only enhance plant growth but also improve germination rates under elevated temperature conditions (Shi et al., 2016). It has been reported that seed priming with silver nanoparticles (Ag-NPs) improves heat stress tolerance in cereal crops by reducing oxidative damage via modifications in antioxidant enzymatic activities (Hossain et al., 2020).

9.8 Policy and governance for climate action

To address the challenges posed by climate change, vigorous and integrated policy packages and governance structures at various levels are required. It is potentially the most long-term problem of our era. Climate change represents a multilateral challenge that operates globally, regionally, and locally all at once, hence it requires a policy counterpart that mobilizes governments alongside international organizations, private enterprises, and civil society. For the above to occur, collaboration amongst these stakeholders is required to develop a holistic and coordinated strategy that encourages structural change toward sustainability. Key elements of this strategy include regulatory policies, financial tools, human resources development, and governance types that encourage both top-down/bottom-up processes (Corfee-Morlot et al., 2009).

The Paris Agreement is an international framework for climate action, at national and regional levels. The Paris Agreement, signed in 2015, is a legally enforceable international climate change convention that was signed by 196 nations and attempts to keep global warming far below 2°C, with efforts towards limiting it to 1.5°C (Dröge, 2016). Countries commit to lowering their release of greenhouse gases by way of Nationally Determined Contributions (NDCs), adapted from their national priorities. This is accompanied by financial support mechanisms such as the Green Climate Fund (GCF) that help developing countries in climate change mitigation and adaptation (Chaudhury, 2020). International agreements like the Paris Agreement are crucial, of course, but achieving their goals will require political will and national policies. Transport, agriculture, waste management, and other industries must be included in comprehensive climate plans. plans may also include carbon pricing mechanisms, such as taxes or cap-and-trade schemes. Local governments are crucial to both emission reduction and climate adaptation because metropolitan regions account for a majority of global carbon emissions. Cities can collaborate to identify common solutions and support ambitious local climate plans by joining networks like

the Global Covenant of Mayors on Climate & Energy and the C40 Cities Climate Leadership Group (Sabine, 2018).

The private sector must play a major role in climate action. Businesses are a significant contributor to GHG emissions, and as such must bear much of the costs associated with the transition to a low-carbon economy. Governments can promote corporate climate action through regulations and incentives for clean energy investment. Many companies are committing to net-zero emissions, lowering their carbon footprints, embracing sustainability goals, and aligning with the ideas of the circular economy. Transparency and corporate responsibility in managing climate risks are further enhanced by reporting standards such as the Task Force on Climate-related Financial Disclosures (TCFDs) (Achenbach, 2021). An essential component of the governance of climate action is climate finance. Projects related to sustainable energy, infrastructure, and adaptability need significant funding. Although the international community has committed \$100 billion annually to aid developing countries, private investment is essential to filling the budget shortfall. To mobilize resources for sustainable development, particularly in the areas of resilient infrastructure, climate-smart agriculture, and renewable energy, public–private partnerships are crucial. Involving civil society is another essential component of climate governance. The extent of the climate catastrophe has been brought to light by NGOs, grassroots groups, and young activists, who have also held corporations and governments responsible for keeping their environmental promises. Incorporating civil society guarantees that climate policies are fair and all-encompassing, especially for underprivileged groups that are disproportionately impacted by climate change. Particularly indigenous peoples offer priceless traditional knowledge for mitigation and adaptation strategies (Atapattu, 2019).

To address transboundary climate challenges, regional cooperation is also necessary. Climate-related phenomena, such as rising sea levels and extreme temperatures do not respect political boundaries. Thus, national efforts can be strengthened by regional cooperation. Frameworks for climate action that encourage collaboration on emissions reduction, climate resilience, and technology transfer have been developed by regional organizations such as the European Union (EU), African Union (AU), and Association of Southeast Asian Nations (ASEAN) (Krampe & Mobjörk, 2018). Lastly, fair transition policies are necessary to ensure that the move to a low-carbon economy does not exacerbate social inequality. The impact of climate measures on workers in industries relying on fossil fuels can be disproportionate. Therefore just transition frameworks must include retraining programs, social protection, and investments in new industries to ensure that the benefits of climate action are shared equitably and that the negative impacts on vulnerable populations are minimized.

9.9 Future outlook and emerging solutions

Climate change already has pronounced effects on plant productivity and ecosystem functioning, which can constrain agriculture and the sustainability of natural

ecosystems globally. This is especially because the changing climate, with increased average temperatures, alterations of precipitation patterns, and an increasing frequency of extreme weather (droughts, floods, and storms) impact plant growth, crop yields, and biodiversity. Temperature variations of even a few degrees can cause damage to sensitive plants, and as the world's temperature rises, many species may become extinct or lose their reproductive habitats. Photosynthesis, nitrogen absorption, and hence plant productivity may be adversely affected by this. For example, some locations would see prolonged droughts with more limited water for crops, while other areas would get excessive rainfall that would cause flooding and soil erosion that would lead to nutrient loss, lowering soil quality and perhaps harming plant health. Climate change also facilitates the introduction and establishment of invasive species and pests, which may displace native vegetation and aggravate biodiversity loss. Tropical and arid ecosystems are most at risk, as they are more susceptible to the severe effects of temperature fluctuations and limited water supplies.

Nevertheless, new solutions are emerging that provide hope for limiting the effects of climate change on plant productivity and ecosystems. Plant breeding and biotechnology are making crops more heat, drought, and pest-resistant. Scientists have been able to use genetic modification and gene editing techniques, such as CRISPR, to make plants resistant to water stress and more water-efficient, as well as improve nutrient uptake. They also promote soil health and biodiversity, reduce carbon emissions, and enhance climate resilience through sustainable agricultural practices like agroforestry, crop rotation, and conservation tillage. These practices offer ecosystem benefits such as carbon sequestration, soil erosion control, and habitat provision by integrating tree and shrub species into agricultural land. In natural ecosystems, conservation and restoration are becoming more and more popular. To enable the migration of animals to better-suited climates, wildlife corridors, and protected areas are being established. In ecological restoration efforts, native plants are frequently employed to restore ecosystem services and functions to damaged areas. Scientists are investigating ways to help ecosystems adjust to changing temperatures, such as the introduction of assisted migration and the reintroduction of animals that have acclimated to the changing climate. Water management innovations, such as rainwater harvesting and drip irrigation, are crucial for controlling water scarcity and guaranteeing sufficient water availability for crops and natural ecosystems.

9.10 Conclusions

Climate change is a significant and complex challenge to plant productivity and ecosystem health, with implications for global biodiversity, food security, and the long-term sustainability of our planet. In this chapter, we have discussed how the warming of the globe and the seemingly simple consequences can strike at so many parts of nature, changing plant development significantly, producing lower crop yields like wheat, and impacting whether forests exist in particular regions. Reduced

productivity of plants under temperature stress, accompanied by water scarcity and changing growing seasons endangers crops but also the physical backbone of both terrestrial and marine ecosystems. Combined with ocean acidification and habitat destruction, the so-called cascade effect of a loss in biodiversity weakens ecosystem health and decreases services for carbon sequestration, and nutrient cycling. Meeting these challenges takes a multiple-discipline, integrative approach. It should be complemented by adaptation measures to increase the resilience of agricultural systems and natural ecosystems for mitigation purposes. Maintaining productivity and conserving biodiversity requires advances in sustainable farming practices, resilient crop development, and restoration of habitats. Good policy and governance are also key to pulling the levers of climate action. Such strategies must be informed by evidence, require international collaboration, and be supported by a policy that delivers sustainable practice across all sectors. In addition to using those methods, research investment and promotion of precision agriculture and ecosystem-based management are crucial to further our ability to handle the dynamic challenges presented by climate change. From here on, the picture of the future is very urgent, we need innovative approaches to tackle climate change in a sustained and coordinated way. To address these challenges with the help of scientific advances, public participation, and sustainable development we could alleviate the impacts on plant productivity and ecosystems. Our ability to respond decisively and cooperatively will determine the resilience and sustainability of nature. Finally, this complex interaction between climate change and ecosystem dynamics requires both urgent and sustained attention. We now need to act on these findings and rise to the challenge by providing smart, practical solutions for generations to come, ensuring not only that plant productivity is protected but also maintaining our ecosystem across the globe. Our roadmap to the future demands a common resolve for environmental stewardship, scientific inquiry, and adaptive management, have to get there slowly so that the feat of a healthy and resilient world can be achieved even amidst such uncertain times with changing climate.

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Harnessing microbes for drought stress mitigation: a promising approach for water stress management in plants

10

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10.1 Introduction

Water is a fundamental component for the development and growth of agricultural crops. With the rise in global climate change, droughts are becoming more frequent and severe, posing substantial challenges to the agricultural sector (Misra, 2014). Water scarcity not only reduces crop yield but also threatens food security, livelihoods, and ecosystems worldwide. Drought poses a significant challenge for farmers every year. It is driven by prolonged periods of inadequate freshwater availability, affecting both human needs and ecosystems. Monitoring drought is difficult due to its recurring nature and its impact across various regions and time periods. This complex stress primarily arises from reduced rainfall and subsequent dry spells. Beyond its impact on food production, drought contributes to a decline in groundwater levels, deteriorates water quality, increases soil erosion, and can trigger other disasters like floods, wildfires, and disease outbreaks. According to the United Nations World Water Development Report 2018, about 55 million individuals worldwide are affected by drought, with an estimated 700 million people potentially facing displacement by 2030 (Ahluwalia et al., 2021). In agriculture produce, grains and legumes are our primary food sources and need a significant amount of water to grow effectively. These crops are particularly vulnerable to drought, which can cause substantial agricultural damage and endanger global food security. As a result, water scarcity is a critical environmental issue worldwide and is expected to become more intense, spread more rapidly, and last longer (Fadiji et al., 2022). To lessen the impact of drought, free-living plant growth-promoting rhizobacteria (PGPR) can be highly beneficial. These soil-dwelling microorganisms inhabit the rhizosphere the area surrounding plant roots and contribute to enhanced plant growth and development. Naturally occurring in soil and root habitats, these microbes have become important allies in fostering sustainable and productive agricultural practices (Khan et al., 2022). These soil bacteria enhance the growth and yield of crop plants through both direct and indirect mechanisms (Singh & Prasad, 2014). These microorganisms boost plant health by producing growth hormones elevating nutrient uptake and defending against pathogens. Recent research has highlighted their potential to reduce the negative impacts of drought. By enhancing root architecture, boosting water uptake efficiency, and activating stress-responsive pathways, PGPR can significantly increase plant tolerance to water scarcity (Vurukonda et al., 2016). This manuscript aims to provide a comprehensive understanding of how these microscopic allies' potential can be harnessed to build more resilient agricultural systems in the face of growing drought challenges.

10.2 Drought stress and its severity: impact on plants

Drought impairs plant growth by reducing physiological activity and disrupting vital processes (Table 10.1). Drought induces numerous molecular, physiological, and biochemical changes at both the plant and cellular levels, that are crucial for stress management (Fig. 10.1).

Table 10.1 Effects of water stress on growth and development of the plant.

Plants	Effect of stress	References
Maize	• Smaller shoots and roots, and reduction in fresh and dry weight. • Reduction in total chlorophyll, and relative water content (RWC). • Reduction in photosynthesis and transpiration rate.	Li et al. (2018)
Alfalfa	• Decline in the rate of photosynthesis, total chlorophyll, and Rubisco activity.	Xu et al. (2020)
Potato	• Reduction in RWC, photosynthesis rate. • Rise in the levels of electrical conductivity, <i>malondialdehyde</i> (MDA), ABA, soluble sugars, proline, and polyamines.	Zhang et al. (2018)
Wheat	• Reduced length, dry, and fresh weight of plant shoots. • Reduction in the weight and quantity of grains per year. • Reduction in chlorophyll a and b, RWC, and membrane stability.	Mustafa et al. (2021)
Tomato	• Reduction in shoot weight, height, chlorophyll a and b, and total chlorophyll.	Gowtham et al. (2020)

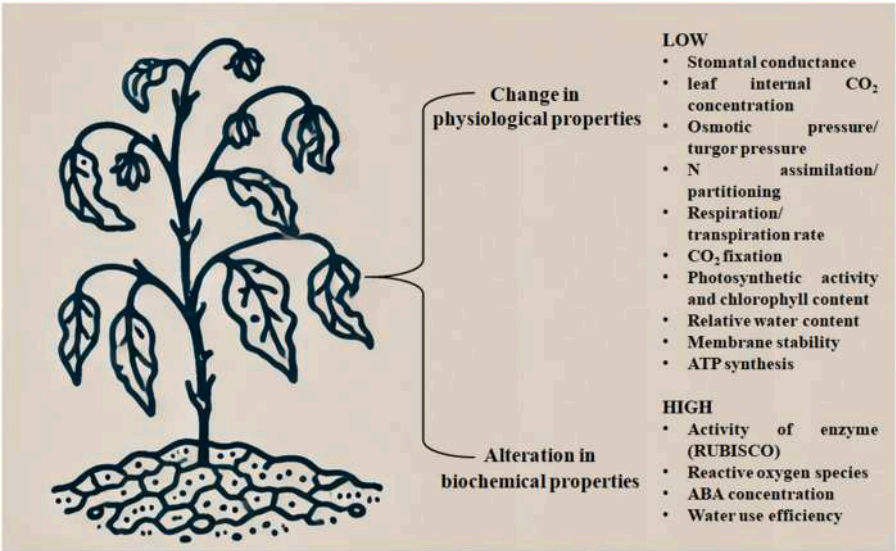


Figure 10.1 Impact of drought stress on the physiological and biochemical traits of the plant.

10.2.1 *Decreasing physiological activity of plants*

Drought stress has a direct impact on agricultural productivity as it reduces water availability (Kumar et al., 2024). Drought stress negatively implication on plant growth enhancement and development by diminishing various physiological activities viz. CO₂ concentration in leaves, transpiration/respiration rate, photosynthetic activities, CO₂ assimilation rate, the water potential of leaves, relative water content (RWC), stomatal conductance, diffusive resistance as well as leaf turgor pressure (Hussain et al., 2018). The reduction in leaf water potential, due to water deficiency directly affects the gaseous exchange through transpiration and stomatal conductance. Stomatal closer gradually increases during drought as retention of water decreases, a first response of plan slowest to prevent water loss via transpiration, which ceases enzymatic activities and slows down the plant's photosynthetic and metabolic activities (Mukarram et al., 2021). For instance, the disintegration of the photo-systems (PSs) I and II restricts critical photochemical reactions that impact the concentration of chlorophyll and carotenoids in plants. The PSII plays a crucial role in ATP production, reduction reaction, and electron transport chain. The decrease in photosynthetic pigments concentration will direct effect on limiting the plant's production by reducing photosynthetic potential (Jarin et al., 2024). Drought stress inhibits transpiration flux, active transport and decreases the membrane permeability, thereby reducing the plant nutrient mobilization. Water scarcity disrupts nutrient ion transport, leading to ion deficiencies, increased oxidative stress, and causes cellular and molecular damage in plants (Sies & Jones, 2020). The increasing oxidative stress in chloroplasts, peroxisomes, and mitochondria reduces the internal CO₂ uptake in green leaves, causing damage at various organizational levels, including membrane destruction, lipid peroxidation, proteins, and nucleic acids degradation (Akhtar et al., 2023).

The following plant physiological activities are affected by drought stress

- Reduction in stomatal conductance.
- Reduction in leaf internal CO₂ concentration.
- Changes in osmotic pressure/turgor pressure.
- Reduction in N assimilation/ partitioning.
- Changes in respiration/ transpiration rate.
- Changes in CO₂ fixation.
- Changes in photosynthetic activity and chlorophyll content.
- Lower RWC.
- Lower stability of the membrane.
- Enhance water use efficiency.

10.2.2 *Alteration in biochemical attributes*

Drought stress also affects various biochemical activities in plants, including influencing photosynthetic pigments, increasing the generation of reactive oxygen species (ROS) and damage by oxidation, enhancing antioxidant production, and impacting starch accumulation, as well as abscisic acid (ABA) and cytokinin production (Sharma et al., 2022). During the vegetative stage in plants, drought

stress reduces the chlorophyll content and efficacy of PSII. In order to decrease water loss from plants and maintain osmotic balance under water-deficient conditions they synthesize various soluble solutes like proline, glycine betaine, amino acids and sugars (Pamungkas et al., 2022). Additionally, the depletion of water level also increases the production of stress hormones such as ABA and ethylene. Increased ABA synthesis lowers the production of cytokinin levels in plants. Water deficiency also increases the ROS generation that adversely affects the macromolecules' stability and membrane integrity (Salvi et al., 2021). In response to increase ROS level in plants, they develop some detoxifying defense system such as superoxide dismutase (SOD), ascorbate–glutathione cycle including catalase (CAT), glutathione reductase (GR), monodehydroascorbate reductase (MDHAR), ascorbate peroxidase (APX), and dehydroascorbate reductase (DHAR) and nonenzyme components like glutathione, tocopherol, ABA, carotenoid and polyphenols (Soares et al., 2019). Drought stress lowers the uptake of nitrate from soil as a result reduction in nitrate reductase (NR) activity. Water scarcity also reduces the storage of carbohydrates at both cellular and organism level. In drought stress, the activity of starch synthesizing enzymes such as granule-bound starch synthase (GBSS), starch branching enzyme (SBE), soluble starch synthase (SSS), and starch debranching enzyme (DBE) inhibits as a result, starch content accumulation can also decrease during plants flowering stage (Lu et al., 2019). These physiological and biochemical responses highlight the plant's resilience strategies under drought stress, striving to preserve core functions, though often compromising the growth and overall yield potential of the plant.

10.2.3 Metabolic modifications

Drought stress triggers a variety of metabolic modifications in plants as they adapt to water scarcity. Plants adapt to drought by adjusting essential processes such as photosynthesis, water regulation, respiration, and the metabolism of antioxidants and hormones (Bhargava et al., 2013). When faced with drought stress, plants typically halt their growth. This reduction in shoot growth lessens the plant's metabolic needs and allows for the reallocation of resources towards producing protective compounds essential for osmotic balance. Additionally, the slowdown in root growth helps maintain the function of the root meristem, which enables quick root regrowth once the stress conditions improve. Inhibition of lateral root growth is also an adaptive response that promotes the development of the primary root, allowing the plant to access water from deeper soil layers (Xiong et al., 2006). Water deficit enhances ABA synthesis, leading to stomatal closure and a reduction in intercellular CO₂ concentration, thereby inhibiting photosynthesis. This inhibition can be reversed if stomata reopen once the stress is alleviated. Conversely, during drought conditions, having open stomata and increased hydraulic conductance can support photosynthesis and the movement of nutrients to the shoot, although this comes with the potential drawback of losing turgor pressure (Chaves et al., 2009). The osmotic adjustment represents another approach that plants employ to cope with drought stress. The production of compatible solutes, including proline and polyols, helps the plant retain cellular water and is essential for sustaining turgor pressure (Blum, 2005).

The development of plants is shaped by the interplay between the assimilation of carbon dioxide through photosynthesis and the release of carbon dioxide during respiration. Respiration is influenced by various processes that utilize the byproducts of respiration, such as ATP for water and nutrient absorption by roots and the transport of assimilates to areas of growth. Other products like NADH and intermediates from the TCA cycle support biosynthetic activities in developing plant tissues, all of which are vital for growth. However, during periods of drought stress, these processes are disrupted, resulting in a decline in respiration rates. In contrast, when water availability is low, respiratory rates may increase, leading to elevated levels of carbon dioxide within leaf tissues (Lawlor & Tezara, 2009). Overall, these metabolic changes reflect the intricate adaptive approach that plants employ to manage drought stress, allowing them to survive in water-scarce environments. However, these adaptations can also disrupt energy metabolism and reduce the synthesis of essential compounds for growth, leading to a notable decline in overall plant performance.

10.2.4 Production of reactive oxygen species

A primary reaction to drought stress is ROS generation, which is considered to be one of the main causes of cellular damage. Elevated levels of ROS can result in partial or extensive oxidation of cellular components, resulting in alterations to the cellular redox balance. Therefore, under stress conditions, it is crucial to maintain control over ROS and their metabolism (Jubany-Marí et al., 2010). The metabolism of ROS is crucial for controlling the oxidative physiology of plants. ROS types studied in plants include superoxide anion ($O_2^{\cdot-}$), hydrogen peroxide (H_2O_2), singlet oxygen ($^1O_2$), hydroxyl radicals ($\cdot OH$), and nitric oxide (NO). Research on ROS metabolism in plants is a leading area of study due to the complex network formed by the differential actions of ROS in various cellular compartments (Kar, 2011). Under normal conditions, cellular ROS levels are kept steady due to a homeostatic balance between ROS production and scavenging. Stressors, such as drought, disrupt this balance, leading to higher ROS production than can be metabolized, resulting in oxidative stress. However, before ROS production exceeds scavenging capacity, an early increase in ROS levels in plants serves as a signal for acclimation or defense responses. The signaling function of ROS is well established, particularly in the realm of pathogen defense, where an oxidative burst initiates defense mechanisms. In fact, ROS are increasingly acknowledged for their positive contributions to growth and progression, alongside their harmful effects during stressful conditions (Lamb & Dixon, 1997).

Drought stress clearly initiates the production of ROS as a key response in plants, typically triggered by hormones like ethylene and ABA, which may also have a regulatory role in subsequent processes. Increased ROS levels can result in oxidative damage, adversely affecting essential cellular components such as lipids, proteins, and DNA, ultimately threatening overall plant vitality. If not effectively countered by the plant's antioxidant scavenging mechanisms, this oxidative stress can worsen the harmful impacts of drought (Xia et al., 2015). To address this challenge, plants have

evolved a sophisticated network of enzymatic and non-enzymatic antioxidants that collaborate to neutralize ROS and preserve cellular balance. Key enzymes like SOD and CAT convert harmful ROS into less reactive molecules, while compounds such as ascorbic acid and glutathione serve as critical scavengers, protecting the plant from oxidative stress and enabling it to survive in challenging environments (Kar, 2011). Ultimately, these adaptive strategies are essential for improving plant tolerance to drought, allowing them to endure and maintain vital functions despite extended periods of water deficiency.

10.3 Biodiversity of drought-tolerant microbiome

10.3.1 Rhizospheric microbiome

The rhizosphere, an essential zone within the soil, harbors a great diversity of microbial organisms including bacteria, fungi, and archaea. The high microbial diversity and density of this region make it very important (Ling et al., 2022). Microbial diversity is vital to the soil ecosystem, establishing numerous interactions with plants. Among these interactions, those occurring in the rhizosphere are particularly vital for the health and development of plants (Upadhyay et al., 2018). The rhizosphere's microbial activity can be one or two orders of magnitude more than the bulk soil nearby and this system is highly responsive and dynamic. In addition to protecting plants against pathogenic microbes as well as from environmental stresses, rhizosphere microbes can help with plant nutrition, water absorption, and growth stimulation through the synthesis of hormones and siderophores (Kukreti & Singh, 2024). Furthermore, PGPRs assist plants in meeting their nitrogen needs by efficiently converting atmospheric nitrogen into ammonia. In addition to nitrogen fixation, plants often face various abiotic stresses, with drought being a major factor limiting the growth and productivity of crops (Fahad et al., 2017; Verma et al., 2021; Gupta et al., 2020). Drought stress causes a range of biochemical and physiological reactions in plants that impact plant overall growth. Rhizospheric microorganisms are vital to plant support through a number of processes. Some of these produce cytokinins, auxins, and gibberellins, which promote the growth of shoots and roots (Khan & Singh, 2021; Singh et al., 2019). PGPR offers a practical way to promote plant development, raise crop yields, and lessen the environmental impact of agricultural activities. Through their metabolic activities, rhizosphere bacteria minimize soil carbon loss while contributing to the carbon cycle in the environment and on earth (Khan et al., 2024). Numerous bacteria, that is, *Pantoea*, *Bacillus*, *Azotobacter*, *Pseudomonas* sp., *Serratia marcescens*, and *Enterobacter ludwigii* are involved in metabolite synthesis, nitrogen fixation, and mineral solubilization under drought stress (Singh et al., 2020; Khan & Singh, 2021; Zhang et al., 2024)). Thus, harnessing the potential of rhizospheric microorganisms, particularly plant PGPR, can be a sustainable approach to enhancing plant resilience to drought and improving agricultural productivity in challenging environmental conditions.

10.3.2 Rhizoplanic microbiome

The innermost edge of the rhizosphere is denoted as rhizoplane, the region where the soil and root surface meet. Plants influence soil fauna and microorganisms directly and indirectly by releasing root exudates and depositing litter, which serve as carbon and energy sources for heterotrophic organisms. Furthermore, plants impose selective pressures that influence the composition of microbial communities in the rhizosphere and rhizoplane (Philippot et al., 2013). The release of various chemicals from plant roots into the surrounding soil is crucial at the rhizosphere-rhizoplane interface, which serves as a vital nutrient hub for plants (Vives-Peris et al., 2020). Unlike bulk soil, the exudates generated by plant roots function as metabolites rich in energy that promote the growth of a variety of microorganisms in the rhizoplane. Secondary metabolites found in the rhizoplane have the ability to serve as signaling molecules, facilitating the communication between plants in close proximity to their roots and soil microorganisms. Furthermore, under particular environmental stresses, the dynamics, compositions, and activities of microbial communities in particular plants are significantly influenced (Zhelnina et al., 2018). The rhizoplane root system is a well-known example of an adaptive feature that drought-stressed plants have produced as a morphological reaction to nutrition and water deprivation (Brown et al., 2017). The bacterial isolates, *Pseudomonas* and *Acinetobacter*, were attached to and colonized the rhizoplane of grapevine and *Arabidopsis* plants. These isolates significantly increased grapevine plant parameters (shoot and leaf biomass, shoot length) as well as photosynthetic activity under aired conditions, with the effects being particularly pronounced for drought-sensitive rootstocks (Li et al., 2015). Thus, the complex interactions between the roots of plants and microorganisms in the rhizoplane are essential for enhancing plant drought resilience, thereby fostering improved growth and sustainability in adverse environmental conditions.

10.3.3 Endophytes

Endophytes are invisible allies in plant tissues that can participate in a variety of development processes that are ultimately advantageous to their host. Plant microecosystems are significantly shaped by endophytes that promote plant development, which are a subset of the rhizosphere microbiome (Khali et al., 2018). Generally, the plant defense system frequently fails to adequately address and manage various stresses (Kandel et al., 2017). Endophytes contribute to plant growth, by performing as natural biocontrol agents and helping the host to withstand various environmental stresses. These microorganisms can produce growth hormones like IAA and aminocyclopropane-1-carboxylate (ACC) deaminase, increase potassium ion uptake in plant tissues, and reduce ethylene levels, providing an alternative mechanism for alleviating stress conditions in plants (Fan et al., 2020). Endophytes can also improve the absorption of nutrients like N, Mg, Zn, S, and P from the soil, enabling nutrient delivery to the host plant to support improved growth and survival. Beneficial endophytic bacteria found in plant tissues offer an encouraging natural method of reducing stressful situations. The type and behavior of endophytes towards plants are influenced equally by edaphic and climatic conditions (Kandel et al., 2017).

Indeed, endophytes represent a valuable microbial resource that should be further explored for agricultural applications. Many of the beneficial growth-promoting species belong to a facultative group of endophytes that typically reside freely in soil but colonize crop plants when conditions are favorable (Gaiero et al., 2013). It would be beneficial to investigate endophytes further for agricultural purposes as they are a rich microbial resource. According to (Gouda et al., 2016), endophytes secrete a variety of bioactive chemicals that aid in colonization and stimulate plant growth and development, hence maintaining a stable symbiotic connection. Nitrogen-fixing endophytes, such as *Novosphingobiumse diminicola* and *Ochrobactrum intermedium* (from sugarcane) and *Bradyrhizobium*, *Kosakonia*, and *Paraburkholderia* (from rice), possess genes linked to nitrogen fixation. Therefore, leveraging the potential of naturally occurring beneficial endophytes for stress management could be a viable strategy to enhance drought resistance and resilience in crop varieties. This approach not only minimizes the need for chemical inputs but also alleviates environmental stress without causing any harmful effects.

10.3.4 Phyllospheric microbiome

The phyllosphere is a zone that is often made up of a plant's aerial sections, primarily its leaves (Mazinani et al., 2017). The external morphological features of plants and the secondary metabolites secreted by bacteria influence the connections between plants and microbes. Furthermore, substances that bacteria and plants emit affect how they interact with one another in the phyllosphere (Harsonowati et al., 2017). Phyllospheric bacteria, both epiphytic and endophytic, enhance plant growth through multiple mechanisms, including hormone secretion, nitrogen fixation, and antibacterial activity. As a result, bacterial populations found in the phyllosphere can function as biostimulants and biofertilizers (Bashir et al., 2021). Due to their intended use in a variety of plant-microbe interactions and their close proximity to the environment, these bacteria must be able to adapt to harsh environmental conditions in order to survive (Tiwari et al., 2024). A population of phytomicrobiome increases a plant's resilience to biotic and abiotic stressors, thereby boosting crop output. PGPR, a crucial component of the phytomicrobiome, increases nutrient absorption, releases antibiotics, and produces chemical signals to enhance plants' responses to biotic stress (Sharma et al., 2022). Plant development is positively impacted by some phyllospheric bacteria that secrete phytohormones and suppress pathogens. Numerous studies have been conducted on the phyllosphere of crops, and it has been shown that the bacterial communities inside these environments differ not only depending on the type of plant but also on the cultivar (Huang et al., 2023). According to Sharath et al. (2021), inoculating cotton seeds with five potent bacterial isolates *Acinetobacter* sp., two strains of *Pseudomonas* (*stutzeri* and *chlororaphis*), *Bacillus mojavensis*, and *Enterobacter asburiae* significantly improved the general growth and drought resistance of cotton plants. On the other hand, Devarajan et al. (2021) found that plants treated with *B. megaterium* PB50 demonstrated better drought stress tolerance by improving RWC, as well as levels of total biochemical

(sugars, proteins, proline, and phenolics), nutrients (potassium and calcium) and phytohormones (ABA and indole acetic acid). Further, a prominent enhancement in the level of stress-related genes such as *Late embryogenesis abundant*, *Responsive to ABA Gene 16B*, *Heat Shock Protein 70*, *Stress-responsive NAC1*, and *Basic-Region Leucine-Zipper 23* was observed in cotton plants.

List of bacteria mitigating drought stress in different crops

S.No.	Types	Bacteria isolates	Crop/plant	References
1.	Rhizospheric bacteria	<i>Pantoea</i> , <i>Bacillus</i> , <i>Azotobacter</i> , and <i>Pseudomonas</i>	Strawberry	Paliwoda et al. (2022)
		<i>Pseudomonas</i> sp. and <i>Serratiamarcescens</i>	Wheat	Khan and Singh (2021)
		<i>Bacillus</i> , <i>Azotobacter</i> , and <i>Pseudomonas</i>	Spinach	Petrillo et al. (2022)
		<i>Enterobacter ludwigii</i>	Rice	(Zhang et al. (2024)
2.	Rhizoplanic bacteria	<i>Pseudomonas</i> and <i>Acinetobacter</i>	Grapevine	Li et al. (2015)
		<i>Stenotrophomonas rhizophila</i> , <i>Xanthomonas retroflexus</i> , <i>Microbacterium oxydans</i> , and <i>Paenibacillus amylolyticus</i>	<i>Arabidopsis</i>	Yang et al. (2021)
		<i>Bacillus</i> strain FAB1 and <i>Pseudomonas</i> strain FAP3	Wheat	Ansari et al. (2023)
		<i>Pseudomonas</i> sp.	Sunflower	Prasad et al. (2016)
3.	Endophytic bacteria	<i>Pseudomonas</i> and <i>Pantoea</i>	Barley	Abideen et al. (2022)
		<i>Paenibacillus polymyxa</i>	<i>Endostemon obtusifolius</i>	Ogbe et al. (2024)
		<i>Acinetobacter</i> sp., <i>Pseudomonas</i> sp., <i>Bacillussafensis</i> , and <i>Stenotrophomonas</i> sp.	Bell pepper	Juby et al., (2023)
		<i>Bacillus subtilis</i>	Wheat	Lastochkina et al. (2023)

4.	Phyllobacteria	<i>Bacillus strain</i> PB3, PB46, and PB50	Rice	Devarajan et al. (2021) Qu et al. (2024)
		<i>Proteobacteria</i> , <i>Deinococcus-Thermus</i> , <i>Verrucomicrobia</i> , and <i>Actinobacteria</i>	Zea mays	
		<i>Pseudomonas (stutzeri and chlororaphis)</i> , <i>Acinetobacter sp.</i> , <i>Bacillus mojavensis</i> , and <i>Enterobacter asburiae</i>	Cotton	Sharath et al. (2021)
		<i>Sphingomonas sp.</i>	Maize	Wang et al. (2022)

10.4 Microbial mechanisms to alleviate drought stress in plant

PGPR significantly aids plants in coping with drought stress. They bolster plant resilience by enhancing root growth and improving nutrient uptake, enabling plants to utilize limited water resources more efficiently. By interacting with both the plant and soil environment, PGPR supports overall plant health, enabling better survival and productivity during drought (Fig. 10.2). This beneficial relationship contributes to more robust plant growth in challenging conditions. This section outlines a list of microorganisms utilized by PGPRs that contribute to plant health and growth under drought situations.

10.4.1 Production of phytohormone

Phytohormones play a crucial role in regulating growth, development, and responses to environmental factors, including both biotic and abiotic stresses like drought (Kasim et al., 2021). The interplay between PGPR and plants involves various physiological changes, particularly in hormonal homeostasis. Certain microorganisms are able to produce and/or influence multiple hormone classes, leading to alterations in hormone concentration, distribution, and signaling, thereby impacting the overall hormonal balance within the plant (Bittencourt et al., 2023). The promotion of plant growth and nutrient uptake by beneficial rhizobacteria has been linked to the production of plant growth regulators such as auxins, gibberellins, cytokinins, and ABA. These microbial regulators influence the levels of plant hormones within plant tissues and have been shown to produce effects akin to the application of external phytohormones (Grover et al., 2021). Numerous PGPR are recognized for their ability to produce auxins, which are crucial for improving root growth and structure. For example, when the auxin-producing strains *Paenibacillus illinoisensis* IB 1087 and *Pseudomonas extremaustralis* IB-κ13-1A were applied to wheat plants, they resulted in enhanced root biomass and higher auxin concentrations in the roots

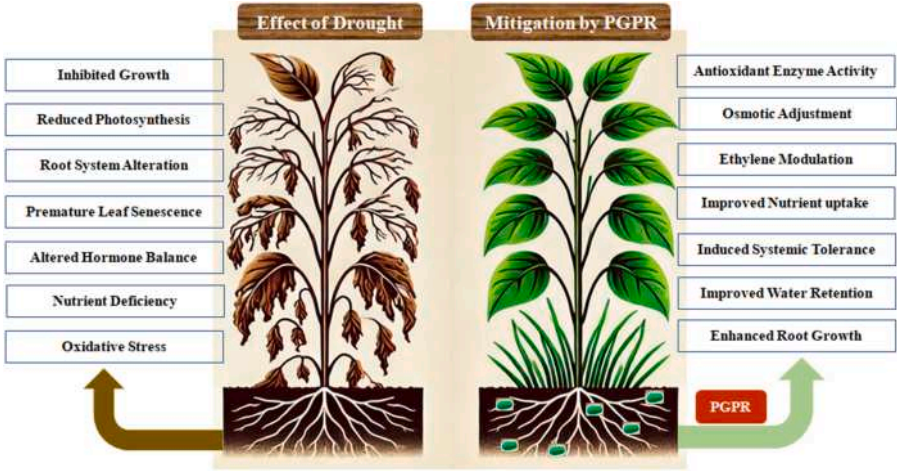


Figure 10.2 Impact of drought on plants and mitigation strategies by plant growth-promoting rhizobacteria.

(Grover et al., 2021). Several studies have highlighted the capacity of PGPR to produce ABA or gibberellic acid or to modulate their levels in plants. ABA is especially recognized for its role in drought stress, wherein elevated ABA levels under water-limiting conditions trigger stomatal closure, thereby reducing water loss (Bauer et al., 2013). Various PGPR, including *Gluconobacter diazotrophicus*, *Azotobacter* sp., *Bacillus* sp., *Herbaspirillum seropedicae*, *Acinetobacter calcoaceticus*, *Azospirillum* sp., and rhizobia, are known to produce gibberellins (Grover et al., 2021). Gibberellins work in synchronization with other phytohormones and regulatory factors to promote both primary root elongation and lateral root extension (Yaxley et al., 2001). The ability of PGPR to produce phytohormones is well-established, and inoculation with PGPR can alter plant phytohormone levels that ultimately influence plant growth. The ability of rhizobacteria to synthesize and release phytohormones is essential for mitigating stress (Table 10.2). These hormones trigger an intricate signaling pathway that aids plants in adapting to their environmental conditions.

10.4.2 Production of aminocyclopropane-1-carboxylate deaminase

Ethylene is a volatile hormone that is naturally generated by almost all plants. It is essential for managing various physiological processes at the molecular level. In addition to its function as a growth regulator, ethylene acts as a stress hormone. When plants undergo stress, such as drought, the levels of internally produced ethylene significantly increase, negatively impacting root development and overall plant growth. Numerous environmental factors and stressors can stimulate ethylene

Table 10.2 The list of plant growth-promoting rhizobacteria induces phytohormone activity in improving plant drought endurance.

PGPR	Plant	Phytohormones production	References
<i>B. amyloliquefaciens</i> <i>S-134</i>	Wheat	Enhanced production of IAA, ICA, and ILA	Raheem et al. (2018)
<i>B. megaterium</i>	Chickpea	Regulation of phytohormones and elevated metabolite levels	Khan et al. (2019)
<i>A. lipoferum</i>	Wheat	Indole acetic acid encourages root development, stimulates the formation of lateral roots, and enhances the uptake of water and nutrients in drought conditions.	Arzanesh et al. (2011)
<i>B. subtilis</i>	<i>Platycladus orientalis</i>	PGPR-induced cytokinin production raises levels of ABA in shoots and enhances stomatal conductance	Liu et al. (2013)
<i>P. putida</i> H-2-3	Soybean	Gibberellin secreted by <i>Pseudomonas putida</i> increased plant growth	Kang et al. (2014)

production, which subsequently impedes plant development ([Abeles et al., 2012](#)). Some PGPR produce a key enzyme known as 1-ACC deaminase. This enzyme is crucial for regulating ethylene levels, as it converts ACC in higher plants into α -ketobutyrate and ammonia. The ACC generated by plants is utilized and decomposed by bacteria that produce ACC deaminase, supplying energy and nitrogen in the process. Furthermore, by degrading ACC, these bacteria help reduce the negative impacts of ethylene, thereby easing plant stress and promoting growth ([Glick, 2005](#)). This PGPR that generate ACC deaminase promote plant growth, particularly under stressful conditions, by managing the elevated ethylene production caused by different abiotic and biotic stresses, including salinity and drought ([Dodd et al., 2004](#)) found that plants treated with bacteria that produce ACC deaminase exhibited greater seed yield, a higher number of seeds, improved nitrogen accumulation in seeds, and recovery of nodulation that had been inhibited by drought stress. Therefore, utilizing the potential of ACC deaminase-producing PGPR presents a viable approach to enhance plant productivity and adaptability under abiotic stress such as drought.

10.4.3 Osmotic adaptation

Plant cells utilize osmotic adjustment as a crucial adaptive strategy to preserve cell turgor and improve their resilience to drought conditions. By regulating the concentration of solutes in their cytoplasm, plant cells can retain water and uphold internal pressure, which helps them withstand dry conditions (Turner, 2017). Osmotic adaptation in plants involves two main strategies: osmo-regulation and osmo-protection. Osmo-regulation maintains cell rigidity by reducing osmotic potential by accumulating solutes. Osmo protection enhances drought resilience by either enhancing the antioxidant defense system or supporting ion homeostasis. Drought conditions can hinder a plant's capacity to synthesize osmoprotectants, leading to a disruption in the osmotic adjustment process and diminishing the plant's resilience to stress (Barnawal et al., 2019). PGPRs play an important role in enhancing the stress tolerance of plants by synthesizing and increasing the levels of various osmoprotectants such as proline, glycine betaine, and trehalose. This boost in osmoprotectants enables the plants to stabilize cellular structures, maintain the turgor of cells, and improve overall resilience to environmental stressors, including drought (Ahluwalia et al., 2021). The buildup of soluble sugars acts as osmoprotectants, serving as an additional adaptive strategy for plants in response to drought. Plants treated with PGPR strains exhibited an increase in soluble sugar levels resulting from starch breakdown, which enhanced their drought resistance, as these sugars function as osmoprotectants during dry conditions (Gowtham et al., 2022). In a similar vein, natural polyamines such as spermine, spermidine, and putrescine are low-molecular-weight aliphatic amines that are widely recognized as compounds that regulate plant growth and offer protection. They play a significant role in the plant's defensive responses to abiotic stresses, particularly drought (Montilla-Bascón et al., 2017).

10.4.4 Generation of volatile organic compounds

Volatile organic compounds (VOCs) in plants are classified into small and large molecules. Smaller VOCs comprise compounds such as ethylene and methanol, while larger VOCs include substances like methyl jasmonate, terpenes, and methyl salicylate. The rate at which these volatile compounds are emitted often correlates with the severity of stress experienced by the plant (Copolovici et al., 2011). Stress-induced VOCs function as signaling agents that prime systemic defense responses and can also enhance plant growth. Additionally, plants can activate their stress defense mechanisms in response to signals from neighboring plants experiencing drought. VOCs offer a swift and nonintrusive approach for detecting drought stress in plants (Timmusk et al., 2014). PGPR can synthesize a variety of VOCs, including ketones, alkenes, and alcohols, which are extremely diffusible in both plant and soil environments (Peñuelas et al., 2014). Microbial VOCs can improve a plant's ability to withstand drought. For instance, when wheat was treated with *Bacillus thuringiensis* AZP2, its drought stress tolerance increased, resulting in a 78% rise in plant biomass and a five-fold increase in survival rates during extreme drought conditions. This enhancement is largely due to a marked decrease in volatile emissions (Timmusk et al., 2014). Specific strains of PGPR emit VOCs that can positively affect plant biomass, improve disease resistance, and increase tolerance to

environmental stresses. Importantly, each bacterial strain generates distinct VOCs that play vital roles in its life cycle, directly impacting plant growth while also influencing the interplay between plants and other microorganisms. Additionally, plants may use certain VOCs as nutritional resources or as signaling molecules for various physiological processes (Bailly et al., 2014). Naseem and Bano (2014) reported that VOCs can enhance nutrient uptake, including sulfur and iron, while also increasing chlorophyll levels and improving photosynthetic efficiency. This ultimately leads to enhanced photosynthesis and greater carbohydrate production. Certain strains of PGPR, like *Pseudomonas aeruginosa* strain Pa2, generate exopolysaccharides (EPSs) that help the bacteria retain moisture in the soil, thereby improving the drought resilience of plants. Ultimately, the multifaceted roles of plant VOCs and the ability of PGPR to produce advantageous VOCs underscore their potential as effective strategies for improving plant resilience and productivity when confronted with environmental challenges like drought.

10.4.5 Production of antioxidants

PGPR enhances induced systemic tolerance in plants experiencing drought stress by activating several mechanisms, such as boosting the antioxidant defense system (Gowtham et al., 2022). Numerous studies have shown that PGPR improves root nodulation and stability of plant cell membranes by regulating phytohormone levels and stimulating the antioxidant defense mechanism, which is directly linked to enhanced drought tolerance in plants (Nithyapriya et al., 2021). Under drought stress, elevated ROS production across various cellular compartments is an inevitable outcome. However, drought stress modifies and reduces the activity of these ROS scavenging enzymes in organelles. As a result, oxidative damage is minimized during periods of drought (Farooq et al., 2012). Antioxidant enzymes that scavenge ROS (viz. APX, GR, DHAR, CAT, MDHAR, POX, and SOD) help the plants to mitigate the harmful effects of excessive ROS by facilitating the oxidation, reduction, and dismutation of O_2 into H_2O_2 . However, drought stress modifies and reduces the activity of the ROS-scavenging enzyme, impairing its ability to regulate ROS effectively (Kusale et al., 2021). PGPRs enhance both the concentration and activity of these enzymes, leading to a reduction in ROS accumulation. For instance, significant increments were observed in scavenging enzymes, for example, APX, SOD, and CAT with catalase activity being up to 1.8 times higher in plants in drought stress treated with PGPR compared to untreated plants. This increase in enzymes responsible for ROS-scavenging suggests that potato plants treated with PGPR were better equipped for drought tolerance (Gururani et al., 2013).

10.4.6 Production of exopolysaccharide

EPSs are key components of soil organic matter and constitute a significant component of the extracellular matrix, often accounting for 40%–95% of bacterial mass (Flemming & Wingender, 2001). EPS produced by microbes are hydrated compounds, containing about 97% water within the polymer matrix. This high water content enables the bacteria to protect from desiccation, particularly under drought

stress, by improving water retention and controlling the dissemination of organic carbon sources (Naseem & Bano, 2014). Ongoing climate change exerts pressure on the microbial community to produce EPS. In addition to promoting soil aggregation, the production of EPS is also attributed to improved water permeability, soil stability, nutrient absorption by roots, fertility, chlorophyll levels, plant biomass, root and leaf surface area, and shoot growth. EPS also plays an essential role in sustaining physiological and metabolic activities during drought stress (Bhagat et al., 2021). Certain EPS-producing bacteria, such as *Pseudomonas*, can endure even in drought conditions because of their capacity to produce EPS (Sandhya et al., 2009). The amount and composition of EPS produced by bacteria are influenced by various factors, including bacterial species, cultivation period, growth stage, and substrate availability. As a result, the diverse components within the EPS confer unique properties, such as improving water absorption and retention in the soil through aggregate formation (Alami et al., 2000). Numerous PGPBs help to maintain plant-water balance, ion homeostasis, and photosynthetic efficiency under drought conditions. The alleviation of stress involves a complex signaling network that emerges from plant-microbe interactions. EPS acts as a nutrient facilitator and an adhesive matrix, helping microbes attach to plants, and plays an important role in supporting plant health under abiotic stress. There is a direct correlation between abiotic stress and the synthesis of EPS by bacterial cells (Sengupta & Dey, 2019; Upadhyay et al., 2012) reported that various indigenous rhizobacteria, including *Bacillus*, *Pseudomonas*, *Brevibacterium*, *Pantoea*, and *Acinetobacter*, exhibit significant plant growth-promoting traits. These bacteria, capable of forming biofilms, have been shown to enhance plant growth and drought tolerance of wheat. Overall, the ability of EPS-producing bacteria to enhance soil properties and plant resilience underscores their potential as valuable allies in sustainable agriculture, particularly in the face of increasing abiotic stressors such as drought.

10.4.7 Mineral uptake

PGPR directly supports plant development and growth by facilitating the uptake of nutrients and enhancing access to vital nutrients (Shah et al., 2021). The absorption of micronutrients from the rhizosphere marks the first stage of their buildup within the plant before they are transported to seeds. PGPRs are essential in dissolving soil nutrients and increasing their accessibility to plants. One of the primary methods by which PGPR enhances mineral absorption is by enhancing the accessibility of vital minerals in the soil. They achieve this through the production of organic acids and enzymes that solubilize minerals and convert them into forms more easily absorbed by plant roots. This process is especially important for minerals that are usually insoluble or bound in the soil, such as phosphates and micronutrients (Etesami & Adl, 2020). PGPR actively supports plant growth by improving resource acquisition, including phosphorus, nitrogen, and essential minerals, through processes like phosphate solubilization, iron sequestration via siderophores, and biological nitrogen fixation. Additionally, they influence plant hormone levels, such as auxins, cytokinins (CK), gibberellins (GAs), and nitric oxide (NO). Indirectly, PGPR boosts plant

growth by triggering induced systemic resistance (ISR), enhancing rhizosphere competition, and facilitating the production of stress-related phytohormones, including jasmonic acid (JA), ACC deaminase and cadaverine (Cad), which is involved in ethylene catabolism (Kloepper, 1981). PGPRs convert atmospheric nitrogen into a form that plants can use, addressing their nitrogen needs. These PGPRs also enhance the availability of phosphorus and other essential minerals, which enables the plants to manage stresses such as drought more effectively (Hasan et al., 2024). Alongside offering mechanical support and aiding in water and nutrient absorption, microbial activity in the rhizosphere influences root development and the availability of nutrients for plants. PGPR stimulates root growth and development, leading to a more extensive root system. Enhanced root growth also improves the plant's ability to explore different soil layers, reaching nutrients that might be otherwise inaccessible (Etesami & Adl, 2020). Therefore, the significant enhancement of plant resilience and productivity, particularly during drought stress, is achieved through the diverse roles of PGPR, which include facilitating nutrient availability, stimulating root development, and regulating plant hormone levels.

10.4.8 Alteration in root morphology and soil composition

PGPR are essential in aiding plants to endure drought stress by altering root structures and improving soil quality. These beneficial bacteria stimulate root growth and branching through the formation of phytohormones such as auxins, cytokinins, and gibberellins, resulting in longer roots with a greater surface area (Kurepin et al., 2014). This improved root system enables plants to reach deeper water sources, which is vital during drought. PGPR also promotes the development of root hairs, increasing the root surface area and improving water and nutrient absorption. A plant's root system architecture (RSA) plays a vital role in adapting to drought conditions. RSA encompasses traits like the number and length of primary and lateral roots, along with root hair density and length. These traits are highly adaptable under water-limited conditions and are important for breeding crops with efficient root systems that support resilience to drought stress. Various transcription factors that control RSA under drought have shown promise in creating drought-tolerant crops (Ranjan et al., 2022). PGPR enhances the efficiency of resource use by optimizing root function at various physiological levels. PGPR support agroecosystems by modifying root characteristics, enhancing crop establishment, boosting resource efficiency, increasing resilience to stress, and promoting better soil structure (Grover et al., 2021). PGPR also boost soil composition by generating EPS that refine soil structure, enhance water retention, and increases soil aggregation, thereby providing a more stable and supportive environment for root growth (Mandal et al., 2022). PGPR also facilitate the absorption of essential nutrients, like phosphorus and nitrogen, by solubilizing these nutrients and making them more available to plants. They synthesize siderophores that bind to iron and make it more accessible to the plant roots, thereby improving the overall nutrient status of the plant (Etesami & Adl, 2020). Overall, PGPR improves root morphology, boosts nutrient uptake, and increases plant stress tolerance, offering a comprehensive strategy for helping plants to manage drought conditions.

10.5 Molecular aspects of drought stress management in plant

10.5.1 Genetic and molecular basis of drought tolerance

Plants undergo various genetic and molecular modifications in drought-stressed conditions that impart tolerance against it. These modifications are regulated by numerous genes and signal transduction pathways that enable the plants to overcome drought stress (Kumar et al., 2018). In plants, there are numerous loci that regulate the drought resistance and each locus has a minor impact. Many plants' morpho-physiological responses, which are the culmination of the combined effect of hundreds of genes, are genetically based on these loci (Mahmood et al., 2019). Under drought stress, the plant undergoes several physiological and biochemical changes that are activated by multiple genes with distinct functions. Drought tolerance is controlled by several molecular and genetic mechanisms including signal transduction factors and functional factors (Tovignan et al., 2020). Signal transduction factors consist of TFs, protein kinases, receptors, and functional factors including proteins involved in metabolism, osmotic adjustment, protein modification and conversion, and ROS trafficking (Wang et al., 2021). Water scarcity stress in plants is associated with various signaling pathways comprised of different proteins, transcription factors, enzymes, molecular chaperones, and various metabolites (Song et al., 2013). Drought stress also triggers oxidative stress at the cellular level through excessive production of ROS, which further activates many stress signaling pathways (protein kinase activated by mitogen, Ca^{2+} , and signaling triggered by hormones) by damaging the cellular membrane (Mahmood et al., 2019). Several transcription factors (TFs) related to drought stress have also been identified in different plants. TFs including DREB, WRKY, bZIP, bHLH, NAC, MYC, MYB family genes and protein kinases such as MAPK and CDPK are involved in cellular signaling and activated during drought stress (Lata et al., 2015). Protein kinases viz. MAPK, MAPKK, and MAPKKK comprise a cascade in respect to both abiotic and biotic stress, which regulates responses through signal transduction. The activation of the MAPK cascade requires sequential phosphorylation, which regulates other TFs, kinases, and proteins, which activates various kinds of responses (Fig. 10.3) (Ichimura et al., 2002). Along with promoting adaptation and survival under stress conditions, drought-responsive genes can also help in the production of phytohormone such as ethylene, ABA, JA, etc. (Kim, 2014). This modifies the amount of Ca^{2+} ions in cytoplasm under the stressed conditions. Ca^{2+} is the common secondary messenger that regulates various physiological activities (Li et al., 2015). Stressed condition also increases ABA concentration in plant cell, which then binds with another protein called SnRK2 and triggers the physiological and molecular changes in response to drought stress. Similar to Jasmonic acid, ABA and its derivatives also initiate signaling pathways that improve drought tolerance in plants (Riemann et al., 2015).

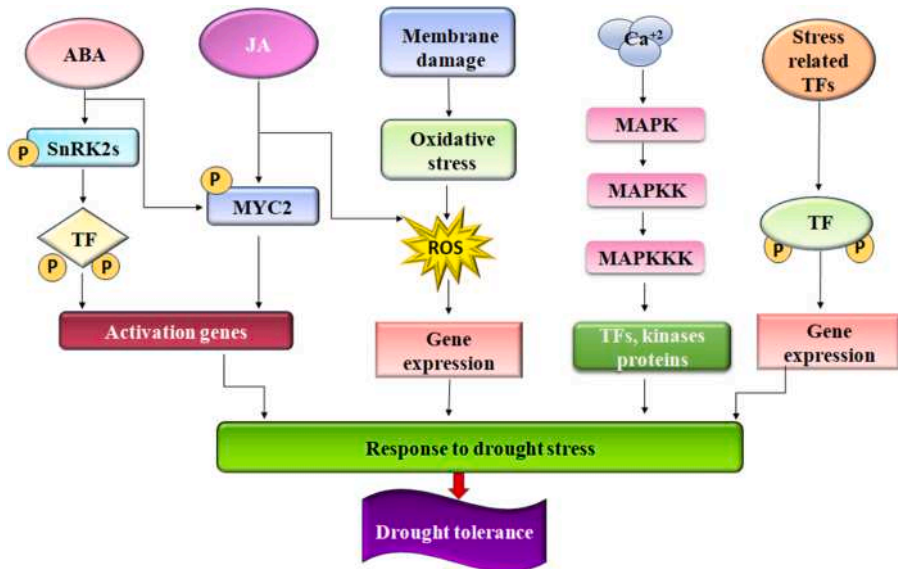


Figure 10.3 Signaling pathways in molecular and cellular processes to enhance plant drought tolerance. The interplay between drought induction, Abscisic-acid (ABA)-dependent and ABA-independent MAPK signaling, along with the interaction of ABA, reactive oxygen species (ROS), and MAPK pathways in plants, in response to drought stress.

10.5.2 Activation of stress-responsive genes through plant-microbe interactions

Stress-responsive gene activation and regulation in response to stress is one of the major processes of tolerance. These genes are expressed and control the synthesis of metabolites that are essential to overcoming adverse circumstances (such as chaperones) during stress conditions (Sahil et al., 2021). Considering the concept, the potential microbes have the ability to control the expression of several genes that help in responding to stressed conditions in different crops, for example, *COX1*, *AP2-EREBP*, and expansin genes reduced stress levels in rice crops (Omar et al., 2021). Vacuolar ATPase, pyrroline-5-carboxylate dehydrogenase, dehydrin-like protein (Cadh), Δ 1-pyrroline-5-carboxylate reductase, CaPR-10, and sHSP are some other examples of proteins and genes linked with microbe plant interactions that are impacted by stress. During drought stress, changes in the expression of these genes result in suboptimal growth and development in plants (Shinozaki and Yamaguchi, 2007). The plant-microbe interaction modifies intricate processes within the plant's cellular system. These interactions enable plant development and cause mitigation of various abiotic and biotic stresses. Microbes like endophytes, PGPR, and PGPF play crucial roles in alleviating drought stress (Evelin et al., 2019). These microbes mitigate drought stress through different mechanisms that include, synthesis of

phytohormone, reducing ethylene production, induction expression genes that produce antioxidants, and upregulation of responses related to dehydration. Additionally, the arbuscular mycorrhizal fungi (AMF) increase the resistance of plants to drought stress by regulating the expression of the 9-cis-epoxy carotenoid dioxygenase (*NCED*) gene. *NCED* is also essential to controlling the ABA metabolism because it catalyzes the oxidative conversion of xanthoxins through epoxycarotenoids (Taylor et al., 2000). Overall, the activation and regulation of stress-responsive genes and proteins through these interactions can aid in mitigating drought stress. Therefore, utilizing these plant growth-promoting microbes is an effective strategy for alleviating drought stress and enhancing tolerance in plants (Shaffique et al., 2022).

10.6 Conclusion and future prospects

Leveraging microbes for drought stress management offers a promising, eco-friendly approach to enhancing plant resilience in water-limited environments. Beneficial microorganisms naturally support plant growth and drought tolerance through adaptive mechanisms, making microbial solutions sustainable and easily integrated into agricultural practices. As climate change accelerates, microbial inoculants are becoming essential tools to enhance plant resilience, supporting growth and sustainability even in adverse environmental conditions. While progress has been made, further research is needed to refine microbial formulations and understand their underlying mechanisms. Incorporating these strategies into agriculture could revolutionize drought management, ensuring food security and sustainability, especially in drought-prone regions. Rhizo-engineering, focusing on optimizing plant-microbe interactions, is gaining attention. PGPR show clear benefits, but the complexity of microbial interactions remains a challenge. Advanced molecular techniques are helping to decode these processes, crucial for enhancing plant adaptation and stress reduction. The future holds the potential for tailored microbial bioformulation to improve water retention and stress tolerance in crops. However, challenges like understanding complex interactions, ensuring consistent results across environments, and scaling up for large-scale agriculture must be addressed through interdisciplinary research and innovative strategies.

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Plant–microbe interaction: a “celestial wedlock” that overcomes climatic disasters for sustainable development

11

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11.1 Introduction

The global population continues to grow steadily, with projections indicating an increase from approximately 7 billion to 8.9 billion by 2050 (Singh et al., 2011). To meet this rising demand, food production must increase by 50%–70% (Tilman et al., 2011). In addition to consistently increasing population, obscure climatic changes also pose a serious threat to agricultural production. To accomplish the nutritional requirements of the burgeoning population and to overcome the drastic climatic changes it is imperative to explore new agricultural practices which boost productivity and enhance resilience. This increase must be achieved in alignment with ecological balance, which requires reducing the use of chemical fertilizers and pesticides (Chakraborty & Newton, 2011). The extensive application of synthetic

chemicals to protect crops from pathogens and pests negatively impacts both the nutritional quality and yield of produce, while also contributing to environmental pollution. Therefore, the need to develop lower-impact alternatives led to the utilization of plant-associated microbial communities, known as plant microbiota (Alori & Babalola, 2018; Kashyap et al., 2017).

Since the colonization of plants on earth, that is, 450 million years ago, microbes have been in association with the plants and diversified over time. The interaction of microbes with plants is found to evolve continuously with a significant influence on the community structure and ecosystem function (Delaux & Schornack, 2021). Furthermore, they are said to be a complex, dynamic, and integral part of the terrestrial ecosystem leading to sustainable agricultural production (Naik et al., 2019; Ray et al., 2020). Plants possess an innate ability to harness the beneficial attributes extended by symbiotic microbes. The ubiquitous interactions within and between microbial communities and their plant hosts form a discrete ecological unit called “holobiont” or “meta organism” (Vorholt et al., 2017).

Therefore, utilizing plant-associated microbes offers a promising solution to balance the rising global food demand with environmental conservation. The plant microbiome is also known to enhance plant tolerance to both biotic and abiotic stresses by activating induced systemic resistance (ISR) mechanisms. Knowing that highly diversified speciation, with increased complexity in interactions, would be an essential need in understanding the role of microbes in their ability to enhance plant growth (Tijjani & Khairulmazmi, 2021).

There exists a vast body of literature on the establishment of microbial communities in a myriad of plant species, while the mode of action remains unknown on how plant-associated microbiota has an impact on the well-being of a plant in general. Thus, the present chapter reviews the varied mechanisms of operation of the microbiota for occupying the plant, the host response of the plant to colonizing microbiota, how microorganisms reprogram cellular processes within the plant and their operations to make agriculture more efficient. It also explains how plants differentiate between beneficial and pathogenic microbes as well as different bacterial species that invade the plant ecosystem. In addition, this chapter will be intended to explain how plants use the benefits brought about by beneficial microbes and fight off the threats provided by pathogens.

11.2 Plant-associated microbes

Plants provide the place for the growth and the proliferation of a diverse array of microbial communities, encompassing protists, fungi, bacteria, viruses, and nematodes (Coleman-Derr et al., 2016; Lundberg et al., 2012). The evolutionary interplay between these microbes and plants is integral to maintaining the stability in ecosystems (Hamonts et al., 2018; Xu et al., 2018). For example, they provide various life-support functions to the plants by colonizing on different surfaces and tissues of such plants, which also entails improving resilience to biotic and abiotic stresses as well as promoting plant growth in addition to enhancing productivity and

nutrient acquisition (Fitzpatrick et al., 2018). An in-depth understanding of the colonization of selective microbial groups on a particular plant genotype will provide a scaffold to strengthen the beneficial traits associated with the microbiota. The microbiome assembly is influenced by interactions between plants and microbes, as well as between different microbial species. Large-scale genome sequencing and the re-colonization of germ-free plants have shown that the members of microbiota associated with hosts are specialized and adapted to their respective plant organs (Bai et al., 2015).

The assembly of microbial communities on plants is deterministic rather than random. The establishment and composition of bacterial communities on plant surfaces are determined by predictable patterns and mechanisms. These factors that influence or shape microbial colonization on plants include the type of soil, specific plant compartment, genotype or species of the host plant, the plant's immune system, plant trait variations and developmental stages, environmental conditions, spatial and temporal dynamics (Hassani et al., 2018). Consequently, it is apparent that some degree of stochasticity must exist in microbial colonization. Notwithstanding the fact that deciphering the microbial diversification, speciation, structural complexity and interactions with their host plant will help us not only to implement strategies for plants, but also enable beneficial microbiome engineering in addition to growth promotion. The potential of plant microbiota to enhance plant productivity and health is realized only if one understands the processes driving the assembly of these communities during the plant development cycle. These mechanisms open up interesting opportunities for manipulating the composition of microbial assemblages.

11.3 Strategic interaction of plant-associated microbes

The plant microbiome has many benefits for the health of plants (Ravanbakhsh et al., 2019). Microbial communities enhance the plant's longevity by promoting growth and productivity, providing protection against pathogens, and strengthening the plant's immune system (Muthamilarasan & Prasad, 2013; Tkacz & Poole, 2015; Turner et al., 2013). Plant-associated microbes perform site-specific functions at different locations within the plant body. Microorganisms within the rhizosphere improve the acquisition of nutrients by the plant. In addition to the gain in crop yield and resistance, the bio-control applications of the microbe prevent excessive environmental degradation as a result of the application of agrochemicals (Larsen et al., 2015).

Microbes reside in different locations inside and on the plant surface (Brown et al., 2020). Their association with plants is categorized broadly into three types: phyllospheric, endophytic, and rhizospheric (Fig. 11.1).

The phyllosphere which includes stems (caulosphere), leaves (phyloplane), flowers (anthosphere), and fruits (carposphere), serves as a significant niche for interactions of microbes with plants (Das & Barik, 2022). Numerous studies have investigated the diversity of microbes related to phyllosphere and rhizosphere (Bashir et al., 2022; Prashar et al., 2014; Sharma et al., 2021). In contrast, the microbiota of other plant

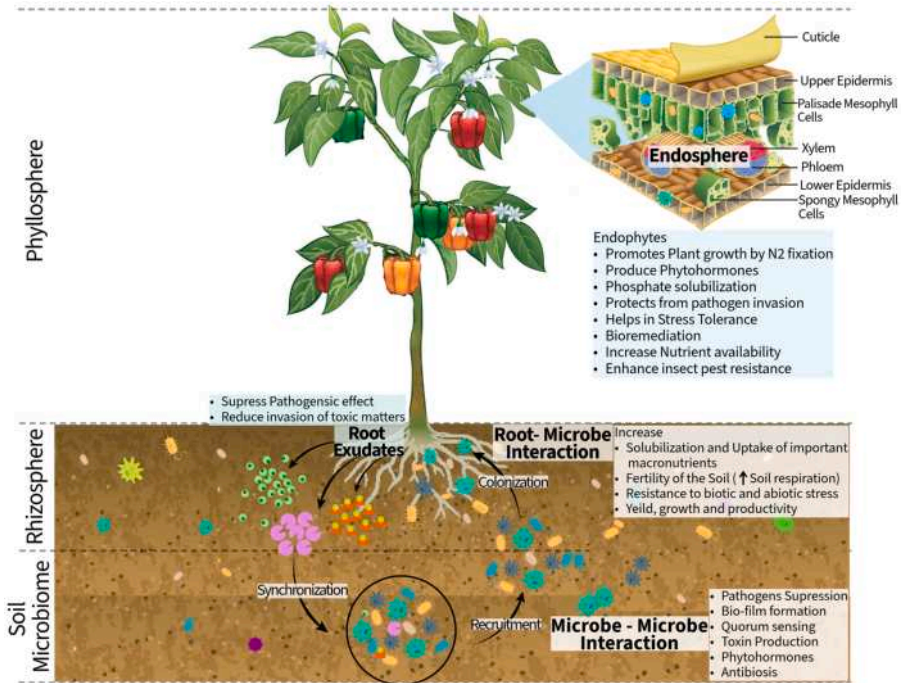


Figure 11.1 Schematic representation of Plant-Microbe interaction. The picture shows the diverse microbial communities inhabiting phyllosphere, endosphere, and rhizosphere of plants. Under stress conditions, plants produce root exudates that attract specific microbes to the plant-root zone. These microbes play a crucial role in mitigating plant stress by enhancing growth, solubilizing phosphate, protecting against pathogens, and improving nutrient uptake.

habitats, like anthosphere, cryosphere, seed habitat, and spermosphere, has been relatively less studied. However, these habitats are of extreme importance in plant fitness as they are directly related to offspring production and involved in the vertical transmission of plant microbiota (Shade et al., 2017). Fungi and bacteria are the most dominant microbes colonizing plant tissues and contribute to the growth of plants besides archaea, nematodes, algae, and protists (Fitzpatrick et al., 2020).

The colonization of bacteria on or within the plant tissues is considered an important factor for plant health and productivity. The three major phyla that make up the bacterial microbiota are Proteobacteria, Actinobacteria, and Bacteroidetes (Chialva et al., 2022). A large number of genera and species of microbes are reported to colonize the phyllosphere and endosphere of their host plants (Bashir et al., 2022; Compant et al., 2021). Notable genera such as *Pseudomonas*, *Sphingomonas*, *Frigoribacterium*, *Pantoea*, *Acinetobacter*, *Enterobacter*, *Methylobacterium*, *Bacillus*, and *Curtobacterium* are commonly found in the carposphere or

phyllosphere microbiota. Normally, the relationship between microbes is synergistic or additive with results supporting growth and disease suppression in plants (Bashir et al., 2022). Despite accounting for an estimated 35.8% of plant microbiota, archaea received less research attention compared to bacteria, likely because pathogenic isolates haven't yet been reported (Müller et al., 2015).

Plants host a diverse array of fungi, including endophytic, epiphytic, phytopathogenic, and rhizosphere-associated species (Ferreira et al., 2021). These fungi show selective interactions with different plant communities. The majority of the plant-associated fungi are saprophytic—feeding on decaying organic matter—some are necrotrophic, acquiring nutrients from dead and mainly degraded, or biotroph, parasitizing live tissues. These interactions can promote plant growth, particularly in the rhizosphere (Hossain et al., 2017). Most of these plant-associated fungi are soil-dwelling and primarily belong to the Ascomycetes, Basidiomycetes, and Oomycetes phyla.

Plants are home to a diverse array of fungi, including endophytic, epiphytic, phytopathogenic, and rhizosphere-associated species (Ferreira et al., 2021). These fungi exhibit preferential interactions with different plant communities. While many of the fungi associated with plants are saprotrophic—feeding on decaying organic matter—some are necrotrophic, deriving nutrients from dead and largely decomposed materials, or biotrophic, feeding on living tissues. These interactions can promote plant growth, particularly in the rhizosphere (Hossain et al., 2017). Most of these plant-associated fungi are soil-dwelling and primarily belong to the Ascomycetes, Basidiomycetes, and Oomycetes phyla.

Although the fungal microbiota of plants has received less attention, culture-independent profiling techniques have revealed a remarkable diversity of fungi inhabiting both above- and belowground plant tissues, primarily from the Ascomycota and Basidiomycota phyla (Hassani et al., 2018). The most commonly isolated genera include *Aspergillus*, *Fusarium*, *Gliocladium*, *Penicillium*, *Phoma*, and *Trichoderma* being the most frequently found across various plant species.

Previous research has shown that specific fungal species can have beneficial effects on different plants, though these effects may vary by species. Custom combinations of these fungi often improve plant performance by enhancing protection at various growth stages and under diverse conditions, while occupying unique or complementary ecological niches (Malgioglio et al., 2022).

Despite the vast diversity of fungi, various species have been identified as sources of bioactive secondary metabolites. While the exact role of these metabolites is not entirely clear, they are believed to significantly contribute to plant defense mechanisms and interactions with other organisms. Consequently, fungal secondary metabolites hold promise for biotechnological applications, serving as prototype molecules for the development of therapeutic drugs (Pusztahelyi et al., 2015).

11.3.1 Mutualistic association between plant-dwelling bacteria and fungi

The interactions between fungi and growth-promoting bacteria in the rhizosphere are particularly intriguing. Several studies have shown that bacteria can thrive on fungal

hyphae, which often form biofilms through various secretions. Similarly, mycorrhizal root exudates serve as substrates that support bacterial proliferation, ultimately converting into nutrients for the plant. Endosymbiosis, especially between bacteria and Basidiomycetes, is a well-established interaction. These symbiotic relationships yield significant benefits, including the production of growth-promoting enzymes between bacterial and fungal hyphae during the senescence stage (Malgioglio et al., 2022). Additionally, arbuscular mycorrhizal fungi (AMF), typically from the phylum Glomeromycota, form a distinct, obligatory mutualistic relationship with host plants throughout their entire life cycle. These fungi rely on the plant for survival and reproduce through asexual spore production (Vorholt, 2012).

11.3.2 Above-ground plant–microbiome interaction

Above-ground plant tissues such as vegetative foliar tissues, leaves, and floral parts harbor diverse endophytic and epiphytic microbial communities such as bacteria (Proteobacteria, Bacterioidetes), actinomycetes, fungi (Ascomycota and Basidiomycota), algae, viruses, and more. Available literature illustrates that a large number of diverse microbes habituated on the phyllosphere are commensals and or mostly nonpathogenic (Sivakumar et al., 2020). The phyllosphere region is supposed to be highly dynamic and exhibits oligotrophy characteristics, including limited availability of carbon and nitrogen. It is also subject to varying physicochemical constraints such as light penetration, UV radiation, temperature, and desiccation (Bringel & Couée, 2015).

Fungi associated with the phyllosphere of forest trees often play saprophytic roles, breaking down leaf litter. Alongside these, other fungi known as latent pathogens are present (Osono, 2006). Microbial colonization varies significantly across different plant tissues and species. For instance, research on tomato plants has shown that the leaves and stems predominantly host *Acinetobacter*, whereas other genera like *Xanthomonas*, *Rhizobium*, *Methylobacterium*, *Sphingomonas*, and *Pseudomonas* are also common in these tissues. When comparing tomatoes to other plants, *Bacillus* and *Pantoea* were more prominent in the lettuce phyllosphere, while *Devosia*, *Dyadobacter*, and *Pedobacter* were dominant on potato leaves, and *Pseudomonas* was prevalent on spinach. In maize, *Sphingomonas* and *Methylobacteria* were the leading bacterial genera in the phyllosphere. Similarly, grapes host a variety of microbial genera in the phyllosphere, including *Pseudomonas*, *Sphingomonas*, *Frigoribacterium*, *Curtobacterium*, *Bacillus*, *Enterobacter*, *Acinetobacter*, *Erwinia*, *Citrobacter*, *Pantoea*, and *Methylobacterium*, while *Pseudomonas* and members of *Enterobacteriaceae* are abundant on apple flowers. Additionally, *Pseudomonas* has been observed as dominant in the floral parts of various fruits, such as apples, grapefruits, and pumpkins.

Variability in microbial communities indicates that microbial colonization is a multi-factorial process and is influenced by host plant species, tissue type, nutrient availability, and local environmental and soil conditions. Thus, the interaction of aboveground plant tissues with their associated microbial communities is largely host-specific and driven by environmental factors and microbial signaling pathways.

These microorganisms can affect the host plant in several ways and potentially enhance growth and on the other hand, defense may trigger disease, promoting yield loss (Nadarajah & Abdul Rahman, 2021).

11.3.3 Below-ground plant–microbe interaction

Soil is a home for many microorganisms that provide sustenance for diverse life forms and stability for the root systems of plants. Over the last couple of years, numerous studies have been conducted on the diversity, density, and composition of microbial populations in the rhizosphere (Nwachukwu & Babalola, 2021). The rhizosphere is the area of soil immediately surrounding the plant roots, and it hosts a wide variety of bacteria, actinomycetes, fungi, and other microorganisms. Root exudates are among the significant inputs such as organic acids, amino acids, fatty acids, plant growth regulators, sugars, vitamins, and others for metabolism that significantly contribute to the availability and nature of these microorganisms close to the roots (Ma et al., 2022).

Rhizospheric microbiome comprises a highly diverse range of bacteria and fungi. Important bacterial species include *Agrobacterium*, *Azobacter*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Cupriavidus*, *Mycobacterium*, *Proteus*, *Pseudomonas*, *Rhizobium*, *Serratia*, *Sphingomonas*, and *Xanthomonas*. Similarly, *Aspergillus*, *Fusarium*, *Penicillium*, and *Trichoderma* are reported to colonize the rhizosphere. Similar to the phyllosphere, rich rhizospheric microbiota is transmitted via vectors in soil, air, or animal hosts (Kumar et al., 2022). These microbes form symbiotic relationships with plant roots and perform critical functions, such as stimulating plant growth, suppressing diseases, managing toxicity, and cycling and utilizing nutrients (Subrahmanyam et al., 2020).

The microbes that colonize the rhizospheric region facilitate the growth of plants through nitrogen fixation, production of IAA and siderophore, phosphate solubilization, enhancement of resistance to biotic and abiotic stresses, activity of 1-aminocyclopropane-1-carboxylate deaminase (ACC), quorum sensing (QS) signal interference, and disease suppression (Benaissa, 2019). Additionally, mucilage and flavonoids secreted from plant roots significantly influence the diversity and functions of the microbes in the rhizosphere (Sugiyama & Yazaki, 2014).

Most plant species (>80%) form associations with AMF particularly within the Glomeromycotina group. Although fewer plant species partner with ectomycorrhizal fungi from either the Ascomycota or Basidiomycota lineages, these ectomycorrhizal species are widespread globally (Smith & Read, 2008; Soudzilovskaia et al., 2019; Steidinger et al., 2019). Specific plant lineages support other types of mycorrhizal fungi; for example, ericaceous plants form associations with ericoid fungi from the Ascomycota, while orchids often partner with orchidaceous mycorrhizal fungi, primarily from the Basidiomycota (Smith & Read, 2008). Additionally, many plant roots host nonpathogenic fungi alongside root pathogens. In desert and alpine regions, for instance, roots are often colonized by dark septate endophytes from the Ascomycota (Porrás-Alfaro & Bayman, 2011). Even in ecosystems like prairies,

where AMF have historically received the most attention, roots frequently harbor hyaline and melanized ascomycetes (Jumpponen et al., 2017).

In contrast to rhizobia, which forms symbiotic relationships specifically with leguminous plants and *Parasponia* species of the Cannabaceae family, AMF establish symbioses with over 80% of terrestrial plants. AMF symbiosis significantly enhances plants' access to inorganic phosphorus, which is typically not readily available to them. For instance, AMF has been implicated in increased productivity in soybean plants. This is associated with increased phosphorus uptake by the host plant (Abdel-Fattah et al., 2014). AMF further ensures the translocation of nitrogen and sulfur to the host plant. The sulfur level is said to be regulated by "sulfate transporter gene" in the host plant (Igiehon & Babalola, 2017). This encompasses the mutual interaction of AMF with root parts of the plants, showing how these relationships affect and impact plant herbivores aboveground, thereby enhancing plant defense activities (Babikova et al., 2014; Harrower & Gilbert, 2021).

These are significantly influenced by biological and physicochemical contents in the soil. For example, factors that contribute to climatic changes like drought and flood have a highly influential impact on the microbial population of the soil. In addition to that, physical factors like soil temperature, pH, atmospheric oxygen, and soil condition have also interfered with the community of microorganisms in the soil (Onwuka, 2018). Chemical constituents from product cycling in soil or through agricultural practices also interfere with the biota of soil. Microbes that can survive under specific stress conditions may benefit the plant because beneficial microbes have been proven to improve soil health and fertility. Soil microbes' complexity is determined not only by the plants but also by environmental factors and other soil constituents (Nadarajah, 2019).

11.3.4 Vertical versus horizontal inheritance of the plant microbiota

Acquisition of plant microbiota found to be processed by two major routes; horizontal transmission—that is, the microbial component is acquired from the neighboring environment- and vertical transmission—by passing it directly from the parent (Shade et al., 2017). Although the nature of these transmission modes in great detail is still undergoing investigation, their contributions in general to the overall richness of seed microbiota have been well established. There are long-term effects caused by vertical transmission on growth, development, and the health of the plants (Gundel et al., 2011). Hurdles in understanding the horizontal and vertical transmission of microbial communities are crucial for realizing reciprocal relationships between hosts and associated microbes. Vertical transmission of microbes highly contributes to the preservation of host-associated microbial communities. Though vertically transferred microbes exist in many varieties of plants, the understanding of ecological mechanisms and dynamic aspects related to the parent-offspring transmission of the microbial communities remains limited. Studies have shown that vertically transmitted microbial communities can persist across two or three generations. For example, research by Kim et al. (2022) identified 29 bacterial and 34 fungal species that were consistently transmitted across generations. Vertical transmission,

particularly from seed to seed, of bacterial or fungal communities has been documented in numerous plant species.

11.4 Endophytes—the hidden microbial world within plants

Endophytes are defined as “microorganisms that inhabit the living internal tissues of plants without causing any immediate or noticeable harm.” Endophytes are ubiquitous and reported in a wide range of agricultural crops. Most likely not a single plant species is devoid of endophytes, each and every plant harbors one or more endosymbionts (Strobel & Daisy, 2003). Evaluating the diversity, distribution, physiology, and ecology of endophytes is a prerequisite for determining the potential of endophytes in enhancing agricultural production.

Endophytes are not a random collection of environmental passers-by but are regulated and specific to the host plant. Endophytes are supposed to find their host either by chemotaxis or electrotaxis (Compant et al., 2010). The colonization strategy differs for each bacterium–host interaction, as each endophytic bacterium has specific preferred sites for colonization. Generally, endophytic microbes occupy a relatively less privileged niche within plants, particularly within the tissues of stems, petioles, roots, and leaves, without causing any noticeable signs of their presence. The microecology of endophytes shows that they can occupy either intracellular or intercellular spaces (Bacon & Hinton, 2001).

Endophytes reside within the apoplastic intercellular spaces, within parenchyma tissue and xylem vessel apoplast (James et al., 2001). Xylem apoplast is considered an ideal place for endophytes as it provides a constant supply of nutrients (Chelius & Triplett, 2001). In the mutualistic association, the internal tissues of the plant offer a safe, stable, noncompetitive, and comfortable habitual niche for endophytes. For getting shelter and food, bacterial endophytes promote plant growth either directly, and/or indirectly by three interrelated mechanisms: phytostimulation, biofertilization, and biocontrol (Bloemberg & Lugtenberg, 2001).

Direct promotion includes (1) degradation of ethylene precursors, 1-aminocyclopropane-1-carboxylate (ACC) using ACC deaminase (Ryan et al., 2008), (2) enhancement of symbiotic nitrogen fixation (Chanway, 1996), (3) production of plant growth regulators (Ahmad et al., 2008), and (4) solubilization of nutrients, especially phosphorus (Glick, 1995). Indirect promotion of plant growth involves biological control of plant pathogens through mechanisms such as the secretion of antibiotics, enzymes that degrade cell walls, hydrogen cyanide, and siderophores. Additionally, it involves competition for nutrients and space (Bais et al., 2004). These mechanisms protect the plants from harmful environmental stresses such as drought, salinity, and heavy metal contamination (Ameen et al., 2024). The close relationship between bacterial endophytes and plants presents a valuable opportunity for their use in plant protection and biological control.

Most endophytes belong to well-known soil microbial genera (Lodewyckx et al., 2002). They primarily enter plant tissues through the root zone, where they may

localize at the entry point or spread throughout the plant. However, they can also infiltrate through aerial parts like flowers, stems, and cotyledons (Hallmann et al., 1997). Endophytes are known to penetrate plant tissue by hydrolyzing cell wall components using enzymes such as cellulase, pectinase, and/or through the wound (Carrim et al., 2006). Of the nearly 400,000 plant species on Earth, none are without endophytes; each individual plant is believed to host one or more endophytic organisms (Strobel et al., 2004). While only a few plant species have been extensively studied in relation to their endophytic biology, endophytes can be classified as either obligate or facultative. Obligate endophytes depend entirely on their host plants for growth and survival (Su et al., 2010), whereas facultative endophytes can exist outside of host plants at certain stages of their life cycle (Rajkumar & Freitas, 2008). Despite the difference in the ecological niche endophytic bacteria utilize similar mechanisms as free-living rhizobacteria to promote plant growth and manage phytopathogens (Compant et al., 2005). For instance, they enhance plant growth by producing auxins like indole-3-acetic acid (IAA), and cytokinin, or by degrading ethylene precursors such as ACC through the action of ACC deaminase (Ryan et al., 2008).

The long co-existence of endophytes and their host plants allows the possibility of horizontal gene transfer, enabling endophytes to produce similar or identical bioactive compounds derived from plants (Alvin et al., 2014). For instance, piperine has been isolated from the endophytic fungus *Periconia sp.*, which colonizes the host plant *Piper longum* L. (Verma et al., 2011). Gibberellins, a phytohormone, have been reported from the endophytic fungus *Fusarium fujikuroi* (Kharwar et al., 2008). Dubey et al. (2020) have highlighted the importance of endophytes in agricultural management. They are genetically able to produce many compounds which aid in the growth of the plants. The mechanisms that enhance plant growth can be utilized to identify species and conditions that maximize plant benefits.

Tomatoes contain different endophyte species: the most abundant ones, in order of abundance, have been reported to be in the genera *Acinetobacter*, *Enterobacter*, and *Pantoea*, although their abundance differs in various plant parts (Dong et al., 2019; Romero et al., 2014). In grapevine tissues, dominant endophytes include *Ralstonia*, *Burkholderia*, *Pseudomonas*, *Staphylococcus*, *Mesorhizobium*, *Propionibacterium*, *Dyella*, and *Bacillus* (Campisano et al., 2014; Dong et al., 2019). Aleklett et al. (2014) have reported that *Pseudomonas* and members of the Enterobacteriaceae family have been isolated from apple flowers, while *Pseudomonas* species are highly dominant in the floral tissues of plants such as apples, grapefruits, and pumpkins. The list of endophytic bacteria is also increasing with the discovery of new species as research work continues to unfold in this fascinating field.

11.5 Plant–microbe interaction in alleviating abiotic stress

The last century has witnessed major climatic changes around the globe, affecting the environmental conditions of the world. There are so many studies highlighting how

these changes have such extreme events, including heatwaves, cold snaps, droughts, flooding, and altered weather patterns, all are harmful to crop production throughout the globe. While plants have developed natural adaptations to manage both biotic and abiotic stresses, they also depend on microbial associations to thrive and protect themselves under these challenging conditions (Fig. 11.2).

However, fluctuations in the climatic conditions have a profound impact on microbial community dynamics thereby threatening crop production and global food security (Barnes & Tringe, 2022; Das & Barik, 2022; Joshi et al., 2023; Singh et al., 2019).

Plants respond to abiotic stress by adjusting various physiological processes: (1) limit growth rate and inhibit cell expansion and division, (2) strengthen the cytoskeleton and cell wall to maintain structural stability, (3) regulate glutathione metabolism, and (4) produce carotenoids (Ghatak et al., 2022; Kang et al., 2022). Stress mediated by environmental perturbations is supposed to trigger the plant, to

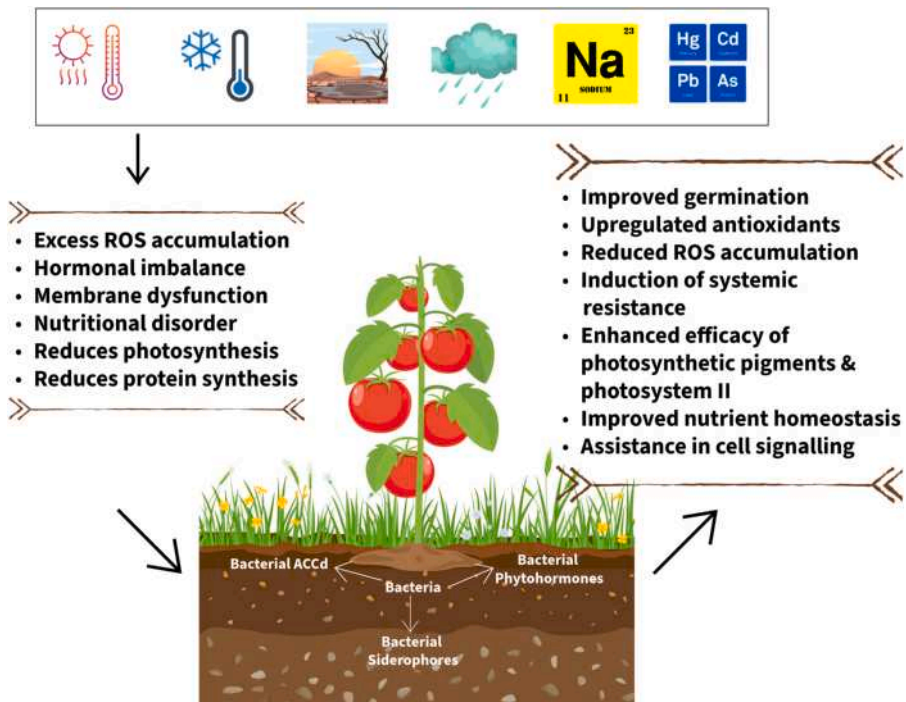


Figure 11.2 Role of microbe in alleviating abiotic stress. Abiotic stresses like heat, cold, drought, salinity, and heavy metals (cadmium, copper, and chromium) significantly reduce crop yields. These environmental factors trigger stress responses in plants, leading to the buildup of reactive oxygen species and decreased photosynthesis, which in turn hampers growth and lowers yields. However, plant–microbe interactions can mitigate these effects by enhancing resource uptake, improving stress tolerance, and overall plant health through different mechanisms.

release chemicals [jasmonic acid (JA), abscisic acid (ABA), salicylic acid (SA), reactive oxygen species (ROS), etc.] that facilitate the habituation of growth-promoting microorganisms (Li et al., 2022). Jasmonates/JA, a group of signaling molecules derived from fatty acids play a key role in regulating growth, reproductive development, and stress tolerance, particularly in defense against herbivores and pathogens. JA facilitates the plant to overcome drought by regulating stomatal movements thereby reducing water loss (Khan et al., 2024). Furthermore, Jasmonates are also crucial in the plant's interaction with beneficial microbes, mediating ISR through pathways dependent on JA and ethylene (ET). Moderate levels of jasmonate signaling often promote mutualistic interactions helping plants from beneficial association with microbes. However, high levels of jasmonate signaling are reported to inhibit plant-microbial interaction (Basso & Veneault-Fourrey, 2020).

Microbes enhance resistance in plants to different wide temperature fluctuations by facilitating nutrient uptake, promoting growth scavenging ROS, reducing cellular damage, and stimulating overall plant health, and are therefore essential for sustainable agriculture (Khan et al., 2019). The microbes produce many significant compounds that enable the plants to overcome stress, which include indole-3-acetic acid (IAA), gibberellic acid (GA), antioxidant enzymes, amino acids, and HSPs. IAA promotes plant growth and tolerance towards stress conditions by activating antioxidant enzymes, regulating gene expression, synthesizing osmoprotectants like proline, and enhancing photosynthetic pigment accumulation (Siddiqui et al., 2017). GAs in particular stimulate plant growth to decrease adverse effects caused due to heat stress as that reduces the levels of stress hormones such as ABA (Bashar et al., 2019). The microbes also evoke the production of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which plays a vital role in scavenging the ROS that are produced during the stress conditions. Amino acids contribute to mitigating injuries caused by abiotic stress by modifying the membrane permeability, increased ion uptake, and action as bio-stimulants (Khan et al., 2019; Prabha et al., 2024). The strategic interaction of soil microbes in plant growth promotion under stress conditions were shown in Fig. 11.3.

Bacillus species are known to upregulate heat shock proteins (HSPs) in maize, making the plant heat tolerant at an early developmental stage. HSPs bound to the thylakoid membrane to protect PDII and to promote the electron transport chain (Ahmed et al., 2018). Soybean inoculated with *Bacillus* species under heat stress conditions were reported to produce IAA, GS, and organic acids (Khan et al., 2020b). Inoculation of plant growth-promoting bacterial consortium has shown a significant rise in maize height, root and shoot biomass, CAT, HSP expression, and chlorophyll content under heat-stress conditions (Ahmad et al., 2023). Khan et al. (Khan et al., 2020a) found that *Bacillus cereus* inoculated tomato seedlings showed increased chlorophyll content under heat stress conditions in comparison to uninoculated plants. The increase in chlorophyll content was due to increased photosynthetic leaf area, better moisture retention in the soil, and higher nutrient supply in the root zone. These factors contributed to a higher net photosynthetic rate and nutrient uptake, N and K, leading to active crop growth and productivity. The synthesis of IAA and GAs, coupled with the scavenging of amino acids and ROS, can promote health and stress resilience in plants.

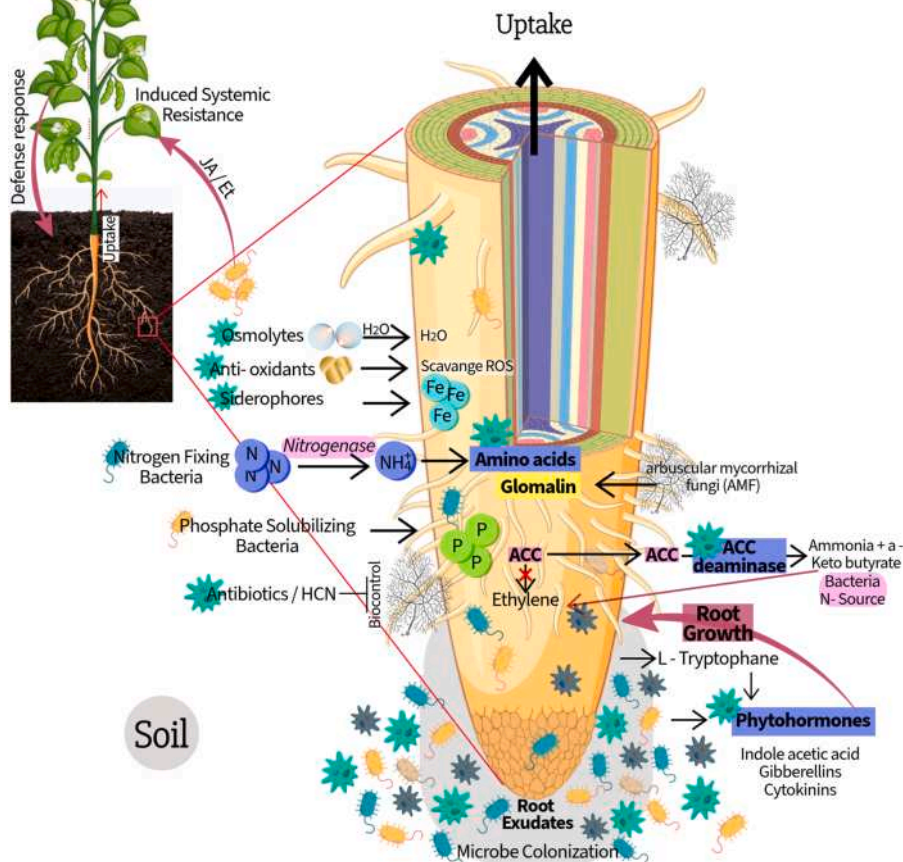


Figure 11.3 Strategic interaction of microbes in plant growth promotion. Different steps involved in plant microbiome assembly. Step 1, Plants release signaling molecules (phenolics, proteins, etc.) via root exudates to attract microbes. Step 2, Microbes respond by mobilizing and colonizing different plant parts as epiphytes and endophytes. The final plant microbiome diversity results from complex signaling between plants and microbes. Microbial activities and root interactions include nitrogen-fixation, phosphate solubilization, iron uptake by siderophores, ACC deaminase activity (reducing ethylene levels), and indole-3-acetic acid production (stimulating plant cell growth). Under salt stress, microbes balance ion content, regulate osmotic balance with osmolytes, and reduce abscisic acid for increased water uptake, prevent reactive oxygen species (ROS)-induced damage by reducing ROS generation and promoting scavenging and stimulate plant growth by enhancing photosynthesis and regulating ethylene signaling. The interactions depicted illustrate the symbiotic relationship between plants and microbes, contributing to soil fertility and overall plant health.

Inoculation of *Bacillus subtilis* in spinach seedlings was shown to increase heat tolerance by producing metabolites like IAA, amylase, and protease which facilitates

adaptation under stress (Li et al., 2023). Halotolerant *Bacillus* sp. Was reported to reprogram the biosynthetic pathways, promoting myoinositol accumulation, and modulating the phyllosphere microbiome to improve plant salt resilience.

The principal role of endophytic bacteria lies in increasing the nutrient absorption rate and in enhancing resilience towards stresses that further increase plant health. Plant growth-promoting endophytic *Pseudomonas* spp. was reported to contribute to stress mitigation by producing exopolysaccharides (EPSs), ACC deaminase, and phytohormones. EPSs play a vital role in drought tolerance in pea plants by osmoprotection (Prihatna & Yan, 2024). EPS also improves soil nutrient entrapment, supporting sustainable agriculture (Paul et al., 2024), and aids in pathogen resistance by blocking root entry (Carezzano et al., 2023). Additionally, EPS from *Glutamicibacter halophytocota* promotes plant growth under salt stress, improving chlorophyll content and antioxidant activity. They further regulate phytohormones, essential for plant stress responses (Chen et al., 2023). Diverse bacterial genera such as *Acinetobacter*, *Arthrobacter*, *Bacillus*, *Corynebacterium*, *Delftia*, *Duganella*, *Exiguobacterium*, *Kocuria*, *Lysinibacillus*, *Methylobacterium*, *Micrococcus*, *Micrococcus*, *Paenibacillus*, *Paenibacillus*, *Pantoea*, *Pseudomonas*, *Psychrobacter*, *Serratia* and *Stenotrophomonas* has been reported to induce stress tolerance in a diverse group of plants (Meena et al., 2023). Auxins produced by PGPR (Plant Growth Promoting Rhizobacteria) regulate root growth and branching, enhance nutrient uptake and improve overall plant vigor; Gibberellins and cytokinins from PGPR stimulate plant growth (Zaib et al., 2023); PGPR like *Azospirillum*, *Azotobacter*, *Bacillus*, *Pseudomonas*, and *Rhizobium* activate the signaling pathways which upregulate nitrogen transporter genes, facilitating efficient nitrogen uptake and utilization (Swarnalakshmi et al., 2020; Yadav et al., 2024). By establishing symbiotic relationships with olive trees, microorganisms enable the plants to better withstand environmental stressors like drought, salinity, and temperature fluctuations, thereby supporting sustainable olive cultivation (Dias et al., 2024).

Under stress conditions, plants require essential nutrients like phosphate, potassium, zinc, and iron for their growth and development. These nutrients are usually unavailable to plants in their directly accessible form. PGPR works to convert these nutrients into forms that can be readily absorbed and utilized by plants. For instance, microbes can solubilize phosphate, mobilize potassium, and produce siderophores to chelate iron, making these nutrients available for the plants. Phosphate plays a very important role in energy transfer across plants through ATP, a component that cannot be avoided, especially during drought or high salt conditions. It also accounts for the production of proteins that help override stress conditions and ensure that the cell membrane remains structural even under stressful conditions. Potassium regulates osmotic balance, an essential determinant in maintaining the water contents within cells subjected to either drought or salt stress conditions. It also induces the enzymes that are involved in the synthesis of stress-related compounds, including antioxidants. These antioxidants defend the plants against oxidative damage. Zinc is a key component of several enzymes and proteins that protect plants from the effects of oxidative stress. It is also involved in the synthesis of ROS-scavenging enzymes that reduce damage caused by environmental stresses like drought, salinity, and extreme

temperature. Iron is essential for the synthesis of chlorophyll and participating in electron transport during photosynthesis. Under stress, iron plays a role in maintaining energy production and reducing oxidative damage by supporting the antioxidant enzyme function (Kumari et al., 2022; Pattnaik et al., 2021).

Mondal and Gera (2024) screened the drought-tolerant mung bean root nodule and identified the presence of *Rhizobium* sp. and *Pseudomonas indica*. Inoculation of mung bean plants with these bacteria resulted in substantial increases in nodule dry weight (56.5%) and shoot dry weight (87.5%) per plant, even under severe drought at 25% field capacity. The study concluded that these drought-tolerant bacterial strains could enhance mung bean crop productivity under drought stress and could be developed as biofertilizers.

A variety of microbial consortia belonging to genera *Achromobacter*, *Acinetobacter*, *Agrobacterium*, *Arthrobacter*, *Aspergillus*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Haloarcula*, *Halobacterium*, *Halococcus*, *Micrococcus*, *Mycobacterium*, *Klebsiella*, *Penicillium*, *Pseudomonas*, *Rhizobium* and *Serratia* can convert insoluble forms of the minerals into the soluble forms, making them known as mineral solubilizers. They achieve this through mechanisms like acidification, chelation, redox activity, exchange reactions, enzymolysis, and production of organic acids and extracellular polysaccharides (Devi et al., 2022).

Not only plant–microbe interaction, microbe–microbe interaction the so-called QS also occurs in some PGPR. QS regulates the formation of biofilms on the root surface, which facilitates other PGPR accumulation and protects the root from environmental stresses. That will improve nutrient uptake, plant health, and retain moisture (Zhuang et al., 2023).

AMF, which form symbiotic relationships with 70%–90% of terrestrial plants, enhance water and nutrient uptake, through their mycelial networks. Furthermore, it also facilitates physiological processes such as photosynthesis, stomatal conductance, and transpiration (González-Mancilla et al., 2024). AMF also secretes a glycoprotein called glomalin, which plays a crucial role in soil aggregation, stability, and carbon sequestration, promoting water infiltration and retention (Channavar et al., 2024). Under drought and temperature stress conditions, several beneficial microbes like rhizobacteria and AMF exert survival strategies by means of the production of osmoprotectants, biofilm formation, changed expression of genes, and horizontal gene transfer, all of which assist the plants to survive water scarcity and temperature fluctuations (Jian et al., 2024; Loiko & Islam, 2024; Wang et al., 2023).

Under stress, plant roots release strigolactones that enhance the high colonization of AMF. This induces local immune response by SA dependent plant defenses locally. To establish symbiosis, AMF suppresses these defenses likely through a family of unknown effectors while promoting ABA to recondition the local defenses (Pérez-De-Luque et al., 2017).

Synergistic effects between plant growth-promoting rhizobacteria, such as *Azospirillum*, *Azotobacter*, *Bacillus*, *Pseudomonas*, and AMF found to improve the health and growth of the plant. For example, *P. putida* with native AM fungi had improved plant growth in cover, cucumber, flax, and sorghum wherein it is clearly

observable that some PGPR may help in mycorrhizal development and performance (Ali et al., 2009; Meyer & Linderman, 1986; Rahimzadeh & Pirzad, 2017). *Quercus variabilis* plant has a symbiotic relationship with fungi *Laccaria bicollis* and *Melanotrichum tuberosum* at low temperatures. The symbiotic relationship significantly influences the physiological performance of the tree by increasing the surface area of the leaves, enhancing the uptake of nitrogen, boosting the efficiency of photosynthesis, and optimizing the use of water. These combined effects help *Q. variabilis* better withstand low-temperature stress (Koza et al., 2022).

Endophytes synthesize phytohormones and bioactive compounds that enhance plant defense against abiotic stresses, including drought (Adiyadolgor et al., 2023). AMF enhance nutrient uptake and withstand abiotic stresses. Clavicipitaceous fungal endophytes in cool season grasses aid in tolerating salt, drought, and heat stress in plants; Dark separate endophytes assist in seed germination and help adult plants survive abiotic stresses like metal tolerance and nutrient deficiencies. Various bacterial endophytes such as *Bacillus* sp., *Pseudomonas* sp., and *Enterobacter* sp. promote plant growth by producing growth-promoting substances and enhancing stress tolerance. Rhizo-endophytic bacteria and fungi play a crucial role in inducing systemic tolerance mechanisms that help plants resist abiotic stressors. Their mechanisms of action include production of growth-promoting substances like auxin, GA, cytokinin, salicylic acid, brassinosteroids, JA, scavenging agents, antistress compounds, trigger stress-responsive genes, and promote the accumulation of suitable solutes in plants when exposed to abiotic stressors like drought, heat, and salinity (Ameen et al., 2024; Bhatt et al., 2024; Eid et al., 2019; Godara & Ramakrishna, 2023). Different endophyte species exhibit habitat-specific adaptations, enhancing stress resistance in various plant types (Abo Nough et al., 2021). For instance, Shekhawat et al. (2020) reported that the root endophyte *Enterobacter* sp. (SA187) enhances plant thermotolerance by reducing the reactive oxygen species (ROS) accumulation and maintaining photosynthesis in wheat plants over three growing seasons without affecting the innate microbial community.

11.6 Conclusions

To conclude, plant–microbe interactions, whether beneficial or pathogenic, are complex that undoubtedly adopt different approaches to facilitate the final association. In recent years, research on plant-associated microbiota has progressed significantly. Study of the plant microbiome reveals the biology and functioning of the host plant. The reservoir of microbes in and around the plant has the additive ecological functions like extending the plant's ability to adapt to varying environmental conditions and changes. The use of molecular approaches based on high throughput sequencing extends the richness and diversity of the plant microbiota. The improved understanding of the plant-microbiome interaction addresses key issues like (1) description of core microbiome across different environments or hosts (2) factors that govern the occurrence of microbial communities, (3) the molecular interactions that occur between the host plant and the symbiotic microbiota, and (4)

the link between symbiont diversity and functions. The interaction of microbes with their host plant illustrates that the proper utilization of suitable microbes is important for maintaining soil fertility as well as it enhances crop productivity and sustainability of agriculture. Looking forward, there are several directions that may fuel research advances on plant–microbe interactions. Furthermore, there are many gaps to fill in characterizing the nature of interaction of microbes with that of the host plant particularly in relation to abiotic stress and disease resistance.

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Impact of climate change on pest and disease outbreaks in agricultural ecosystems

12

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12.1 Introduction

Anthropogenic activities are polluting everything on the Earth that has been preserved for millions of years. Human beings have been contaminating air, water, and soil on an unprecedented scale, especially after the Industrial Revolution. Though Earth's climate has undergone changes from time to time, human interventions have been resulting in substantial variations in the global climate (Pachauri & Reisinger, 2007). Unmatched developments in various fields of science in the past few centuries helped us to exploit natural resources, but not without predicaments. It has been said that development is double-edged; pollution, destruction of ecosystems, global warming, and climate change have become inevitable. Global warming and greenhouse effect are resulting in the melting of polar ice which ultimately is leading to rising sea levels with unparalleled consequences especially affecting coasts. This man-made disaster pattern seems only to increase in the coming years.

Water scarcity, decrease in the area available for cultivation, diminishing soil fertility, disease, pest outbreaks, etc. are among the major bottlenecks in increasing the production and achieving food security. Global warming further complicates already intricate agro-ecological system. Since farming is mainly climate dependent, unpredictable changes in climate is wreaking havoc. Climate change impacts agriculture by influencing pests, pathogens, and weeds, as well as by affecting the efficacy of plant protectants and other management measures. To cope up with changes in regional climate many of the plant species are changing their preferred latitude and altitude (Parmesan & Yohe, 2003). Crops that prefer cooler climate and prone to drought are retreating to higher altitudes and cooler areas like apple production shifting to the higher elevations in the Himalayas. Scarcity of water, heat waves, and unseasonal rains due to disturbances in monsoon, unpredictable floods, and recurrent droughts are adding to the worries, challenging our food security and making the livelihoods of farmers even harder. In a striking example of effect of climate change on agriculture in Kerala, harvesting season of honey from honey bee colonies has been shifted from the first week of January to February, burdening the apiarists with one

month of additional expenditure. This is caused by the change in leaf shedding season of rubber plants from December to January which affects the foraging of honey.

Changing climate is projected to bring out substantial changes on phenology, behavior, occurrence, and population of various pests in the coming years. This may comprise shifts to higher altitudes and latitudes, changes in life cycles starting early in Spring and continuing to late Autumn seasons, enhanced growth rates due to higher temperatures, more generations per year, changes in migration pattern, shifts in interaction with other species or natural enemies (Root et al., 2003; Sutherst, 1991). Severe rainstorms, longer periods of droughts, unexpected floods, and unusually high temperatures significantly affect pest and disease incidences. To withstand climate change, any species must adapt to new conditions early on by constantly evolving or change their distribution to places with congenial climate. Intense rainfalls are expected due climate change which may reduce populations of small and soft bodied insects transiently.

It would be an arduous task to precisely predict how diseases and pests will behave to changing climate; nonetheless, it is certain that many species of useful insects would disappear, while novel vectors, virulent pathogenic races, decrease in natural enemy population, extension of pests and diseases to new territories, etc. are likely to occur. In addition to this; pests and diseases that are causing negligible losses may start causing significant economic damages. Wider geographical range of disease incidences, sudden outbreaks of diseases, changes in the efficiency of management measures, increased crop losses are the probable consequences of climate change.

There has been comparatively limited research on the effects of global warming on the incidence and progression of plant diseases, though most of the researches focus on the impact of one atmospheric component or weather factor on the pathogen, host or the interaction between two under experimental conditions. Nonetheless, available information indicate that climate change could affect disease incidence through altering host physiology and resistance, can affect the host plants, pathogens as well as host–pathogen interactions.

12.2 Impact of climate change on pest incidence

Climate change will have significant consequences on pests in the ecosystem processes and may change to great extent (Cornelissen, 2011). These changes include (1) expansion to new geographical areas, (2) shortening of generation time and more number generations in a specified time period, (3) changes in phenology (4) alterations in phenological synchronization among crops, pests, and their natural enemies, (5) enhanced population sizes, and (6) higher risks from invasive species and outbreaks of minor pests (Wang et al., 2022). Indirect effects include changes in host systems, breakdown of resistance, effects on weeds, vectors, etc.

12.2.1 Effect of higher temperature on insect pests

Insects, being poikilothermic organisms, are highly sensitive to environmental fluctuations particularly changes in temperature. If the species has a wider

geographical distribution, these changes may affect insects to a lesser extent. Changes in temperature will directly influence the rate of survival in winter especially in the northerly latitudes and increase in temperature will possibly prolong duration of summer benefiting reproduction and growth. Although photoperiod is the major signal for seasonal synchrony of insects in the temperate regions, their thermal requirements vary during different seasons (Bale et al., 2002).

12.2.2 Effect of elevated carbon dioxide

As CO₂ concentration increases, the carbon-to-nitrogen (C:N) ratio of plant biomass increases (Rao et al., 2014), which will force to pests to become more gregarious to derive required amino acids. Increase in CO₂ has been positively correlated to the multiplication of *Nilaparvata lugens* (Brown planthopper). In addition, the secretion of honey dew also increases when CO₂ concentration increases (Prasannakumar et al., 2012). Pests will try to compensate by the increasing rate of feeding to derive required amino acids and to cope up with the lower nutrient status of the host (Rao et al., 2014). Compensatory feeding has been shown by insects like leaf chewers, to mitigate decrease in the quality of leaves higher CO₂ concentrations. Larval duration may also get extended because of lesser nutrition derived from host plants (Coviella & Trumble, 1999). Nonetheless, this behavior is often insufficient as many insects show substantial decrease in their growth (Lindroth, 1996).

12.2.3 Effect of drought on the incidence of pests

The incidences of *Bemisia tabaci* (Genn.) and *Tetranychus urticae* Koch. were higher on drought-stressed cowpea plantations as compared to the nonstressed ones. Similarly, pod borer *Etiella zinckenella* Treitschke, the incidence showed an obvious increase on drought-stressed cowpea plants (Abdel-Galil et al., 2007). Longer periods of drought can result in reduced uptake and increased nonuniform translocation of systemic insecticides within plants. This will eventually decrease pesticide efficacy and increase the chances of pests evolving behavioral resistance to insecticides. Target pests can develop the capability to sense and avoid plant tissues with higher concentrations of systemic insecticides and the behavioral resistance may become widespread as a result of climate change (Khodaverdi et al., 2016).

12.2.4 Impact on the geographical distribution of pests

Temperature influences the growth, development, reproduction, abundance, geographical distribution, etc. of any insect pest. Because of the increase in temperature many insect species are expected to pull out from locations that become unfavorable and move to regions with better climate. Thus, pests accustomed to temperate regions will withdraw to higher elevations and latitudes searching for more suitable climate. A rise in temperature by 1°C would result in 200 km northwards or 140 m upward (altitude) expansion of geographical range of certain species (Parry & Carter, 1989). *Chilo suppressalis* (Asiatic rice borer or striped rice stemborer) had been estimated to move approximately 300 km north if the temperature rose by 2°C (Morimoto et al., 1998).

It is vital to continuously monitor pests in relation to their reproduction, population growth, habitat change, migration, etc. to predict their appearance and to devise effective management measures.

12.2.5 Impact on the dispersal of pests

Spread of problematic pests and diseases to new locations has been occurring due to climate change events like hurricanes, cyclones, thunderstorms, and floods and aggravated by the evergrowing global trade and international travel. Altered wind patterns due to climate change can disperse wind-borne pests and inoculum of pathogens to new areas. For instance, post mega floods of 2018 in Kerala, notorious Giant African snail (*Achatina fulica*) appeared in new regions. Continuous rains and flooding have upped the chances of alarming invasions of the Giant African snail in previously unseen territories causing serious concerns.

12.2.6 Impact on the growth rate of pests

Temperature plays a vital role in growth, development, and reproduction of insect pests. In general, higher temperatures will hasten the development of insects like European corn borer, Colorado potato beetle, onion maggot, and cabbage maggot, which brings up the possibility of added number of life cycles per annum, which will ultimately lead to more damages (Rao et al., 2009). For example, in India, *Helicoverpa armigera* on red gram (Srinivasa Rao et al., 2016) and *Spodoptera litura* on peanut (Rao et al., 2015) are expected to have two to three extra generations due to higher temperature.

12.2.7 Impact on the reproduction and multiplication of pests

Climate change will increase the number of generations of pests per year by promoting greater intrayear breeding as well as enhancing the population growth. If we analyze the example of potato–aphid–virus relationship; high temperatures, especially during early season, help viruliferous vectors to infest seed potatoes much earlier in Northern parts of Europe, which contaminates the stocks and diminishes their use for crop production (Robert et al., 2000). Higher temperatures promote sexual populations with augmented variabilities and with better resistance to pesticides creating problems in the management (Malloch et al., 2006). Aphids also depend on specific microbes like bacteria in the gut, which influence their fitness-related traits as well as resistance to pathogens and natural enemies (Ferrari et al., 2004), bringing out the possibility of more complex trophic interactions possibly affected by changes climate.

Global warming would affect voltinism of insect pests possibly to different extents. In multivoltine species like aphids, increase in temperatures would aid enhanced development rate, ultimately resulting in additional generations per annum. Tropical insects are comparatively vulnerable to variations in temperature as at present they are surviving adjacent to their temperature optima (Deutsch et al., 2008). This indicates that even if there is a 2°C–3°C increase in temperature, ambient temperature

may surpass optimum range leading to detrimental effects. For instance, egg laying and the time required for the development of *Rhopalosiphum padi* have been reported to reduce under higher temperature coupled with higher CO₂ content (Moreno-Delafuente et al., 2020).

12.2.8 Changes in overwintering behavior

As temperature increases there may be delay in the onset of hibernation, which can prolong the duration of pest infestation ultimately leading to higher yield losses. Pests can also infest sooner in the spring season after mild winter. Minimum temperature has profound effect on the geographical range of an insect compared to maximum temperature. Global warming can enhance the ability of pests to overwinter at higher altitude due to the increase in temperature. For example, aphid infestation on barley has been found to be inversely proportional to average minimum temperature in January month and total rainfall in February (Chander et al., 2003).

12.2.9 Changes in the migration pattern

Climate change influences migration pattern and can spread the distribution of the pest to northern latitudes, eventually expanding territory of pathogens and insects. Due to rising temperature, in combination with mounting heat stress on crops, these areas can witness sudden outbreaks of pest and disease incidence, higher usage of plant protectants, resulting in low yields and higher cost of cultivation.

12.2.10 Effects on the fitness-related behavior or traits

Sitobion avenae (English grain aphid) and *Rhopalosiphum padi* (bird cherry-oat aphid) exhibit heat-escape behavior that is affected due to temperature stresses brought out by global warming (Ma & Ma, 2012). Similarly, the development time and fecundity of *R. padi* decreased under higher CO₂ content in combination with higher temperature (Moreno-Delafuente et al., 2020). Changes in temperature might also influence the interaction among insect pests like leaf-miners. A temperature-arbitrated competitive segregation interaction between two leaf-miner species has been observed (Rodríguez-Castañeda et al., 2017).

12.2.11 Effects on the community structure

Pest community structure can get significantly affected due to global warming and climate change-related adverse events. For example, high temperatures shift the hierarchy of dominance of *Rhopalosiphum padi* and *Sitobion avenae* (Zhu et al., 2021).

12.2.12 Impact on interspecific and multitrophic interactions

Apart from direct influence on pest species, climate change can also affect interactions at interspecific level in the ecosystem. If we consider infestation of *Lipaphis erysimi* and *Myzus persicae* on Rapeseed-mustard, *L. erysimi* is major

during severe winters while *M. persicae* is serious during mild winters (Chander & Phadke, 1994). With rising temperatures, *M. persicae* incidence will increase. Similarly, pest–natural enemy interactions will also be affected by the changes in climate. In Japan, an increase in winter temperature due to global warming is expected to result in higher infestations of striped rice stemborer (*Chilo suppressalis*) in the coming years (2031–50) compared previous decades (1981–2000) converting less harmful pests to become pests of serious concern (Yamamura et al., 2006).

Rising night temperatures have been found to change predator–prey relationships (Ma et al., 2021b). For example, Xing et al. (2003) reported the effects of higher CO₂ concentration and soil moisture content on population dynamics, egg-laying, development of *Rhopalosiphum padi*, and its host (wheat). The development time and egg laying of *R. padi* decreased under higher CO₂ content in combination with higher temperature (Moreno-Delafuente et al., 2020). Giving high nitrogenous inputs could improve the nitrogen content in the plants as well as egg-laying capacity but could not completely counter the ill-effects of higher CO₂ on the overall fecundity of the aphid and nitrogen content in the plants. Similarly an increase in the maximum temperature resulted in higher mortality of old nymphs of *Nilaparvata lugens* (brown planthopper). However, in case of *N. lugens* higher CO₂ enhanced egg-laying capacity and secretion of honeydew by Guru-Pirasanna-Pandi et al. (2018). Gu et al. (2019) observed that the temperature tolerance of *Cnaphalocrocis medinalis* (rice leaf folder) improved after undergoing 2–3 generations of heat selection. It also exhibited behavioral thermoregulation like selecting lower surface of rice leaves for egg laying under high temperatures (Bodlah et al., 2017) and constructing overlapping multileaf shelters, whereas under optimum temperatures, they preferred to make longitudinal shelters formed from single-leaf (Bodlah et al., 2019).

12.2.13 Impact on host plants

Due to the “fertilization effect” from increased CO₂ concentrations, plant biomass, and overall crop yields may increase (Ainsworth & Long, 2005) with possible chances of higher food production. Yet, there are also indications that crop yields may reduce due to higher temperature and water scarcity (Anwar et al., 2007; Torriani et al., 2007). Higher CO₂ content causes build-up of carbohydrates in the leaves due to enhanced carbon assimilation and the rising C:N ratio (Robinson et al., 2012). From insects’ perspective, this will lead to decreased nutritional quality of leaves as “N” is considered a limiting nutrient. Furthermore, shifts in chemical defenses in plants are also reported under increased CO₂ that would affect herbivorous insects (Robinson et al., 2012). Elevated CO₂ concentrations in the atmosphere can also influence interactions among insect pests and host plants. A rise in CO₂ can bring about changes in the biochemical nature of host plants like a decrease in nitrogen content in the leaves and increase in carbohydrates as reported by Bezemer and Jones (1998) after going through data obtained from 43 insects.

12.2.14 Impact on phenology

The influence of temperature on insects varies depending on the host plants also. Phenological effects even vary for same insects that feeds on different host plants.

Global warming has a noteworthy impact on phenology of host plants, affecting annual events like bud breaking, blossoming, commencement of growing season etc. that will eventually affect pests and pathogens. Such effects may be less pronounced on insects with wider host range and having ability to feed on low quality ones. The rising CO₂ content in the atmosphere is projected to incite greater reduction in the nutritional status of C₃ plants, compared to C₄ plants. In response to this, insects may intensify their feeding unequally on C₃ hosts (Barbehenn et al., 2004; DeLucia et al., 2008). Insects which exhibit an array of compensatory feeding capabilities may be able to cope up with phenological changes induced by global warming (Bale et al., 2002). Chewing insects might be unaffected or decline, but not expected to increase whereas population densities of sap sucking insects are supposed to augment due to an increase in CO₂ content in the atmosphere (Whittaker, 1999).

12.2.15 Impact on natural enemies

Whether natural enemies will also multiply like pests due to the climate change is not well understood. The fitness of natural enemies can definitely get affected due to variations in herbivore quality and size, brought out by the changes in CO₂ and temperature on plants. The vulnerability of pests to predators and parasitoids can get reduced because of added plant growth or shifts in the lifecycles of pests against changes in the phenology of plants. At the third trophic level, the effects of higher CO₂ concentrations on the herbivore–plant relationship may further affect the performance of natural enemies (Stiling et al., 2002) altering development, growth, multiplication, and parasitization/predatory preference of natural enemies. As opposed to this, due to warmer climate, there will be instances where the effectiveness of natural enemies and/ vulnerability of prey to natural enemies will increase (Thomson et al., 2010). According to Kiritani (2006), high temperatures favor parasitoids compared to their hosts. For example, uneven heating at night produces contrasting effects on wheat aphids and their natural enemies (Ma et al., 2021b). On Aspen trees interplanted with the Birch trees, populations of natural enemies showed significant positive correlation with increased CO₂ levels and inverse correlation against elevated O₃ (Percy et al., 2002).

Due to rising temperatures, pests may complete life cycles at faster rates, which will eventually reduce the time available of parasitoids and natural enemies, significantly affecting reproduction and survival of natural enemies (Gutierrez et al., 2008). This will compromise the management measures involving natural enemies. By selecting or breeding natural enemies with temperature tolerance will address this issue to a great extent. In contrast, because of the changes in nutritional status of plants, if pests take longer duration to develop, they will be more susceptible to natural enemies due to longer exposure time to predators and natural enemies.

12.3 Impact of climate change on plant pathogens

Plant pathogens and the process of infection are significantly influenced by climate change, variations in CO₂ concentration in the atmosphere, temperature, and rainfall

(Wang et al., 2022). For instance, weather factors like temperature, moisture content or relative humidity, CO₂ concentration, wind, and a combination of the above factors, significantly affect the outbreak of diseases in wheat (Shang et al., 2018). Due to climate change occurrence and severity of several diseases are expected to intensify due to climate change (Wakelin et al., 2018). At the same time, global warming might also restrict the incidences of diseases like wheat powdery mildew (Matić et al., 2018) and can have deleterious effects on the evolution of pathogens like *Zymoseptoria tritici* causing leaf blotch (Chen et al., 2017).

Spore traps in the United Kingdom have established variable effects of climatic factors on the dispersal of various fungal spores, with some species exhibiting negative responses to moisture while having positive responses to temperature (Hanson et al., 2022; Sadyś et al., 2016). Populations of plant pathogenic fungi, like *Alternaria*, *Fusarium* and *Venturia*, showed a positive correlation with temperature, while were largely unaffected by rainfalls, in soils from a number of natural ecosystems (Delgado-Baquerizo et al., 2020). Though higher latitudes have less pathogen load at present, they are supposed to face bigger risks from soilborne diseases in the coming future. Species richness of plant-pathogenic fungi as well as Oomycetes has been found to be significantly affected by climatic factors in pristine grasslands, but these influences were not prominent in disturbed areas (Delavaux et al., 2021).

12.3.1 Effect of higher temperature

Temperature has a profound effect on the lifecycle of a pathogen and subsequently influences pathogenicity, disease epidemics, and dispersal of plant pathogens (Bebber, 2015). Several pathogens are also relatively sensitive to fluctuations in the temperature (Rodriguez-Algaba et al., 2020). Ongoing global warming will affect pathogens and extreme climate events, like the long spells of droughts and extreme temperature, hurricanes, and torrential rains will affect plant pathogen infections as well. In lower latitudes, the severity of diseases like rice blast will increase under high temperatures and higher atmospheric CO₂ (Viswanath et al., 2017). In contrast, it is also projected that the intensity of leaf blast will reduce in Japan (Duku et al., 2016; Yoshida et al., 2015). Simulations based on models suggest that increasing temperatures will favor higher incidences of blast diseases in cool subtropical zones, like northern parts of China, while the incidences will come down in warm humid subtropics and humid tropics (Luo et al., 1995). In North America, higher mean temperatures during winter increased severity of disease caused *Phytophthora* spp. in American chestnut causing significant lethality (Gustafson et al., 2022). Early snowmelt has been linked to increased snow blight (*Phacidium infestans*) in pine trees (Barbeito et al., 2013). High temperatures coupled with high humidity is correlated with higher disease incidence in case of late blight of potato caused by *Phytophthora infestans* and Phoma stem canker disease of oilseed rape. Sheath blight disease exhibits higher rate of infection under elevated temperatures of 28°C–32°C, and therefore increasing temperatures can promote the rapid growth of hypha. Higher temperature is linked to severe incidence and outbreak of several diseases like stack

burn, leaf smut, Bakanae disease, sheath spot, grain spot, and false smut (Matić et al., 2021).

Heating of wheat litter on experimental basis enhanced plant–pathogen species richness, but not their comparative abundance (Wahdan et al., 2020). In the same line, in oak canopy, the abundance of pathogenic fungi diminished with experimental warming (Faticov et al., 2021). Temperature response models for 80 plant pathogenic fungi and oomycetes revealed that the risk of infection is likely to follow predicted variations in crop productivity under climate change scenario (Chaloner et al., 2021). Accordingly, infection risk is found to go up with latitude, possibly restraining any yield benefits brought about by the climate change (Saunders, 2021). Data on cardinal temperature indicate that temperature responses, especially in *Phytophthora* spp. are evolutionarily labile (Chaloner et al., 2020). An assessment of model outcomes involving only monthly temperatures, with results using hourly estimates of humidity and temperature produced similar disease risk estimates, suggest that, at large spatial scales, the most vital factor in future for changing disease risk temperature is probably temperature (Chaloner et al., 2021).

12.3.2 Effect of elevated carbon dioxide

Under elevated CO₂ conditions, infection by Barley Yellow Dwarf Virus) enhanced the nitrogen content of wheat in the above ground parts, in comparison to noninfected wheat plants, leading to reduced performance and phloem ingestion of aphid vector *Rhopalosiphum padi* (Trębicki et al., 2016). Hormone concentrations in host plants and subsequent resistance responses are affected by CO₂ concentrations in the atmosphere which ultimately affects host–pathogen interactions. Increased expression of Jasmonic acid-responsive genes under higher CO₂ concentrations reduced susceptibility to necrotrophic pathogen *Botrytis cinerea*, while also increased susceptibility to the hemibiotroph *Pseudomonas syringae* pv. *tomato* (Zhou et al., 2019). In wheat, reduced effectiveness of host defense pathways under higher CO₂ concentrations and decreased resistance against *Fusarium graminearum* and *Zymoseptoria tritici* infections resulting in higher severity of Fusarium head blight and blotch respectively have been reported (Váry et al., 2015). Similarly, under higher CO₂ concentrations, the severity of powdery mildew on cucurbits caused by *Sphaerotheca fuliginea* increased (Khan & Rizvi, 2020). However, reduction in severity of downy mildew of soybean (*Peronospora manshurica*) has been also observed (Eastburn et al., 2010).

Due to changes in the leaf surface characteristics instigated by higher CO₂ concentrations, the incidence of rust disease in Aspen trees increased (Karnosky et al., 2002) whereas severity of brown spot disease in maple trees decreased (Velasquez et al., 2018). Similarly, higher CO₂ concentration has been found to increase the number of lesions due to leaf blast and severity of damage caused by sheath blight. This implies that losses from infection and outbreaks of sheath blight disease and leaf blast will increase in the coming days as CO₂ concentrations in the atmosphere keeps increasing (Kobayashi et al., 2006). Elevated CO₂ levels can increase severity of diseases caused by fungi in rice and wheat, probably by

suppressing host immune response or changing density of trichomes and stomata (Váry et al., 2015). Under higher CO₂ concentrations and elevated temperatures, diseases caused by *Fusarium* spp. in salad crops and *Blumeria graminis* (powdery mildew) on barley showed a significant increase (Chitarra et al., 2015; Gullino et al., 2017; Mikkelsen et al., 2015). It is hard to generalize effect of elevated CO₂ levels, as the effects seems to vary depending on the host-pathogen and their interactions. Though, responses to high temperature and elevated CO₂ levels vary with the pathosystem considered, relations between the two drivers are frequently positive (Gullino et al., 2018).

12.3.3 Effect of drought

Soil is extremely complex dynamic ecosystem, each influenced and affected differentially by changes in climatic variables (Pritchard, 2011). This can affect plants through effects on roots, crop canopy (Pangga et al., 2011) as well as by affecting pathogens, weeds, and beneficial microbial communities (Newton, Gravouil, et al., 2010). Several diseases caused by *Fusarium* spp. and *Macrophomina* sp. become severe during drought. Severity of diseases like sharp eyespot caused by *Ceratobasidium cerealis* can decrease under minimum tillage practices due to the increase in population of competitors and antagonists (Burnett & Hughes, 2004; Yarham & Norton, 1981).

Overall, necrotrophs hasten drought-induced tree mortality by exhausting resources as a result of compartmentalization and repair processes, whereas diseases caused by biotrophs are anticipated to lessen under drought due to a strong relationship between the tree nutritional status and pathogen performance. Nevertheless, if biotrophs could invade trees under stress, they might cause much more severe drought induced effects on trees as they drain carbohydrate reserves that are crucial in tolerance against drought conditions (Oliva et al., 2014). Drought and soil moisture stress enhances the risk of plant diseases like onion white rot (*Sclerotium cepivorum*), pea root rot (*Aphanomyces euteiches*), wheat crown rot (*Fusarium* spp.), wheat take-all (*Gaeumannomyces graminis* var. *tritici*), grapevine black foot (*Dactylonectria* spp.), brassica black leg (*Leptosphaeria maculans*), and charcoal rot of sorghum (*Macrophomina phaseolina*). On the contrary, drought brought down the severity of rot caused by *Sclerotinia sclerotiorum* in kiwifruit and red needle cast disease of Radiata pine caused by *Phytophthora pluvialis* (Wakelin et al., 2018). Similar reports are also available in grapevines against *Xylella fastidiosa*, which is a fastidious bacterium inciting Pierce's disease (Choi et al., 2013). Dry root rot (*Macrophomina phaseolina*) of Bengal gram is favored by long periods of drought (Rai et al., 2021). Longer durations of drought will probably intensify take-all disease of wheat caused by *Gaeumannomyces graminis* var. *tritici* and *Fusarium* crown rot (Wakelin et al., 2018). Drought reduces the resistance responses of host plants which intensifies potato yellow vein virus disease and yellow vein symptoms (Vasquez et al., 2022). Prolonged drought causes water stress which predisposes forest trees to dieback disease incited by *Phytophthora* (Desprez-Loustau et al., 2006; Hossain et al., 2019; Ryu et al., 2018). Nonetheless these effects seem specific to particular soils and it would be difficult to attribute to climate change alone.

12.3.4 Effect of higher moisture content and humidity

With increase in relative humidity, an overall increase in the severity of diseases caused plant pathogenic fungi can be expected (Romero et al., 2022). For instance, severity of *S. sclerotiorum* in lettuce (Mamo et al., 2021) and stem rot caused by *Phytophthora sojae* have been found to increase under high humidity conditions (Tada et al., 2021). In Bangladesh, unusually humid and hot conditions because of the climate change, coinciding before the harvest, have been attributed to the outbreaks of wheat blast due to *Magnaporthe oryzae triticum* (Islam et al., 2019). Excess rainfalls can promote higher incidences of Fusarium head blight (Song et al., 2019). Also, high humidity and high temperature conditions favored incidence of *B. cinerea* in grapes (Ciliberti et al., 2015). In contrast, lower moisture conditions increase pathogen load and aggravates severity of rice blast (*Magnaporthe oryzae*) and bacterial scab (*Streptomyces* spp.) in potato (Bidzinski et al., 2016; Johansen et al., 2015). In rice as many of the diseases caused by fungi become severe in humid conditions, incidence and severity of infections on leaf caused by fungi are forecasted to intensify under higher moisture conditions (Duku et al., 2016).

12.3.5 Impact on the geographical distribution of pathogens

Climate change events like increased temperature, high soil moisture etc. can further extend the range of plant pathogens across new geographical territories. The presence of favorable climatic conditions, lack of antagonists and susceptible hosts can promote the unchecked multiplication in new geographical areas. In this regard, many plant pathogenic fungi are expected to extend to new territories, as the global mean temperature increases. Global warming can extend the range of several plant pathogens which are at present restricted by need for overwintering, like *Puccinia graminis* f. sp. *tritici* causing stem rust of wheat (Ma et al., 2015). On the contrary, with constant increase in summer temperatures over 30 years, local extinction of rust (*Triphragmium ulmarie*) infecting *Filipendula ulmaria* (meadowsweet), has been reported (Zhan et al., 2018). Pathogens like *Phytophthora infestans*, are supposed to be little impacted by warming temperatures due to their lower thermal preferences (Sparks et al., 2014).

Experiments, along with models, suggest that the pervasiveness of major soil-borne pathogenic fungi like *Alternaria*, *Fusarium*, *Phoma* and *Venturia* will most probably increase due to the ongoing global warming (Delgado-Baquerizo et al., 2020). Recurrent and severe incidences of *Neufusicoccum parvum* and *Botryosphaeria dothidea* have been attributed to the climate change (Batista et al., 2022). Pathogens can also adapt and evolve to infect new hosts and/or become much more virulent to counter plant protectant chemicals, break down host resistance, or they form new races or strains through mutations or interspecific hybridization. For example, hybridization events between *Phytophthora uniformis* and *P. multiformis* lead to the formation of a hybrid *P. alni* species that is causing severe decline of Alder trees across Europe (Mizeriene et al., 2020).

12.3.6 Impact on the dispersal of pathogens

Rosenzweig et al. (2005) reported the spread of plant pathogens to new locations by hurricanes. Spores of rust disease of soybean is most likely introduced to United States from Brazil by hurricane Ivan (Fones et al., 2020) and is causing serious yield losses. Moreover, diseases and pests can reduce the export potential of an agriculture produce due to quarantine restrictions and Embargo, depriving farmers export earnings like in the classic example of Karnal bunt (Anderson et al., 2004).

12.3.7 Impact on the multiplication of pathogens

High temperatures often reduce the incubation time of the pathogen, consequently increasing the pathogen population and inoculum available in a growing season. In wheat, the latent period of *Puccinia recondita* f. sp. *tritici* (leaf rust) is going to shorten which may result in the increased severity of leaf rust outbreaks (Caubel et al., 2017; Wójtowicz et al., 2020). Due to the increase in crop biomass and more cycles of infection over additional growing days, global warming will result in bigger rust pathogen populations, which may speed up the evolution of novel races on wider spatial scales (Chakraborty et al., 2010).

12.3.8 Impact on pathogen interspecies occurrence

Climate change is predicted to enhance the populations of soil-borne plant pathogenic fungi (Delgado-Baquerizo et al., 2020). An increase in temperatures can result in the evolution of new strains or races of pathogens that have better ecological fitness and have more virulence (Cohen & Leach, 2020, Fisher et al., 2020, Newbery et al., 2016, Velasquez et al., 2018). The intensity of head blight caused *Fusarium* in wheat is predicted to become severe, because milder *F. culmorum* that is favored by cool climate is getting dominated by more virulent *F. graminearum* favored humid and warm climate (Parikka et al., 2012). Likewise, older strains of *Puccinia striiformis* have been replaced by more virulent and temperature-tolerant novel strains resulting in severe outbreaks of wheat rust disease in Australia, Europe, and the United States (Vidal et al., 2022; Walter et al., 2016).

12.3.9 Impact on host plants

Severity of pests and disease infestation is inversely correlated to the inherent resistance of plants. Nonetheless, host resistance is also significantly altered due to climate change events like higher ambient temperature, prolonged periods of heat and drought. Higher concentrations of CO₂ can result in increased biomass, altered chemical compositions (lower concentrations of toxins, increase in tannins/phenols), altered leaf thickness, physical topography, epicuticular waxes, etc., which will in turn affect infestation by pests as well as pathogenesis. Higher temperature can also breakdown temperature sensitive resistance. Higher CO₂ can result in increased plant biomass and canopy density with microclimate more congenial to pests and disease outbreak. In future, irrigation water as well as its quality will also become a limiting factor for agricultural production. Repeated irrigation can also increase soil salinity,

which will affect pathogen, pest, and interactions with microbes indirectly. For instance, pathogen spores from salt- or water-stressed plants can possess higher infectivity (Wyness & Ayres, 1985). Further, drought and cold stresses as well as stress-relief measures also have been found to influence the expression of resistance to diseases (Goodman & Newton, 2005; Newton & Young, 1996). Availability of macro and micronutrients also affect pests and disease incidence on which climate change have an indirect influence, as pathogens show differential response to the availability of various nutrients (Walters & Bingham, 2007). It will be difficult to predict how climate change will further affect and complicate this.

Plant immunity responses can get suppressed at high temperatures, resulting in increased infection and disease severity (Cheng et al., 2019). In Arabidopsis, synthesis of salicylic acid, a hormone involved in plant defense pathways has been found to be suppressed by high temperatures, as the activation of major immune transcription factors like CBP60g gets impaired (Kim et al., 2022). In rice, higher temperatures enhance the production of abscisic acid as well as responsive genes, which is linked to increased severity of bacterial blight, whereas silencing abscisic acid pathways at higher temperatures, correlated with improved resistance (Cohen et al., 2017). Similarly, in rice, Jasmonic acid synthesis and signaling genes induced by *Magnaporthe oryzae* resulted in greater susceptibility to rice blast disease at high temperatures (Qiu et al., 2022).

Extreme weather conditions can induce pathogenic fungi to form populations with variations in fitness and pathogenicity, ultimately prompting host plants to evolve with novel gene products to mitigate the threat from the pathogens (Gregory et al., 2009). Effects of climate change on multiple components like interactions between pathogens and insects, pathogens and plants (Juroszek & Von Tiedemann, 2013); three-way interactions among viruses, pests, and host plants, and among between plants, natural enemies, and insects (Juroszek & Von Tiedemann, 2013) have been studied. Coinfection of pathogen and pest disclosed that powdery mildew infection reduced infestation by aphid (*Sitobion avenae*); similarly, *Rhopalosiphum padi* preferred healthy leaves that had not been infected by necrotrophic pathogen *Parastagonospora nodorum* (Asalf et al., 2021).

12.3.10 Impact on natural enemies/antagonists

The biocontrol efficacy of *Ampelomyces quisqualis* was significantly higher under increased CO₂ concentrations of 800–850 ppm (Gilardi et al., 2016). However, antagonists can become more vulnerable and their efficacy can decrease due to climate change. Regardless of the IPM strategies adopted to manage diseases and pests, they will also affect natural enemies and beneficial organisms as well as succeeding IPM components (Stenberg, 2017).

12.3.11 Impact on nematodes

Like other pathogens, plant pathogenic nematodes (PPNs) are also prone to the changes in the climatic factors. Low soil moisture due to prolonged periods of droughts will adversely affect nematodes in the soil. Similarly, even minor variations

in temperature shows significant impact on the growth and progression of lifecycle of PPN (Evans & Perry, 2009). Under low temperature development is slow, while faster development takes place under higher temperatures (Maleita et al., 2012; Trudgill et al., 2005; Tzortzakakis & Trudgill, 2005). Warming due to climate change can increase the number of generations per season by shortening duration of life cycle, thereby increasing the risk of damage (Trudgill et al., 2005). For example, in coffee plantations of Brazil, global warming and related events can worsen the damages from root-knot nematode *Meloidogyne incognita* races 1, 2, and 4 by the increasing number of generations per season in the future (Ghini et al., 2008). Higher population density of *Trichodorids* sp. under higher CO₂ concentrations in soils with low nitrogen content has been observed (Hoeksema et al., 2000). The sensitivity of soil nematodes to CO₂ enrichment under various cropping system demonstrates nematode channel ratio [the ratio of the number of bacterivorous and fungivorous nematodes in a specific soil sample] to be significantly enhanced in wheat and sugar beet cultivated under higher CO₂ conditions in Germany (Sticht et al., 2009).

Higher CO₂ concentrations (500 ppm) lead to warming of canopy by about 2°C, which considerably enhances the population of rhizospheric PPNs, at the same time reducing the overall diversity nematode (Wang et al., 2021). It is projected that an increase by 1°C in the mean temperature would extend the geographical range of Longidorids and Trichodorids that are capable of transmitting virus, further northward by roughly 160–200 km in Great Britain (Neilson & Boag, 1996). Invasion of virus transmitting PPNs to new geographical areas poses will threaten crop productivity and further increase cost of production. In India, *Meloidogyne graminicola* thought to be a pest of upland paddy, has been reported from many of the major rice growing areas including direct seeded paddy and hill ecosystems (Dutta et al., 2012). (Prasad & Somasekhar, 2009) reported that *M. graminicola* has the potential to cause greater losses in paddy under elevated CO₂ concentrations (700 ppm) compared to ambient CO₂ concentrations (400 ppm). Similarly, increased abundance of PPN at higher temperatures has been reported from Kashmir valley (Nisa et al., 2021). An increase in temperature also resulted in the spread of *Bursaphelenchus xylophilus* (pine wood nematode) as well as its vector *Monochamus alternatus* at global level, where America, northern parts of Europe and Asia are especially vulnerable (Hirata et al., 2017; Li et al., 2022). Increasing temperatures will also change the status of several nematodes. Higher soil temperatures result in reduction in the population of *Globodera pallida*, but favors *G. rostochiensis* in the southern parts of United Kingdom (Jones et al., 2017). Likewise, in Russia spread of *G. rostochiensis* has become more menacing because of warming due to climate change (Pridannikov et al., 2022).

12.4 Impact of climate change on post-production, storage, and processing

Climate change can also affect the quality of final produce due to increased temperature and higher CO₂ that can decrease protein and nutrient contents as well

as influencing moisture content, growth of molds, production of mycotoxins further impacting overall quality. For storage as well as transport, around 12% moisture is desirable in the grains. If moisture content exceeds this, strategies such as delayed harvest, aeration or drying will have to be employed to reduce the moisture content, which further increase the cost. Unseasonal rains coinciding with harvest can increase moisture content in the grains and greatly reduce the keeping quality. For instance, if contaminated wheat grains are stored at higher moisture levels, concentration of Deoxynivalenol; a potent Mycotoxin called as DON goes up manifold within few weeks (Birzele et al., 2000). If the moisture content is not brought down to required levels in wheat, it can also result in aflatoxin contamination (Anwar et al., 2008; Saleemullah et al., 2006). Throughout the world higher content of Deoxynivalenol as well as other toxins produced by fungi are concern in the grains that are weather-damaged or not properly dried (Blaney et al., 1987). In addition to ingestion while taking food, fungal spores and mycotoxins can get easily inhaled during agricultural activities like drying and threshing.

Off late there has been preferenthe ce for organically grown food among consumers, due to growing concerns over excessive use of plant protectant chemicals. Organic food has advantages as well as disadvantages in relation to synthetic pesticides, environmental contaminants, animal feed contaminants, mycotoxins, toxins, biopesticides and the foodborne diseases of humans and animals, etc. (Magkos et al., 2006).

12.5 Impact of climate change on mycotoxins and pesticide residues

Under climate change scenario, the presence of residues of pesticides and mycotoxins in food is of serious concern in Europe (Miraglia et al., 2009). Due to rainfalls coupled with raising temperatures at the time of anthesis, the severity of *Fusarium* Head Blight (FHB) is predicted to aggravate (Madgwick et al., 2011). It may not happen in the areas where precipitation is expected to decrease or change pattern of distribution. Nevertheless, quality of wheat may decrease due to a rise in temperature, even in comparatively dry locations like the Southern parts of Australia. (Luo et al., 2009). If there is drought after flowering, loses due to crown rot (*Fusarium* spp.) becomes serious as pathogen hinders flow of water and nutrients to spikes which leads to the formation of “white heads” having no grains or shriveled grains (Chakraborty et al., 2006; Luck et al., 2011). On the contrary, warm and humid climate during anthesis favors *Fusarium* head blight causing complete or partial blighting of the head, production of mycotoxins, reduced harvest coupled with deterioration in quality of grains. Higher concentrations of Deoxynivalenol produced by *F. graminearum* in various grains has been positively correlated with high humidity (Andersen et al., 2015; Qiu et al., 2016). Similarly, presence of mycotoxins like Trichothecene, Zearalenone reduces the grain quality and is detrimental to human beings and animals (Desjardins, 2006). With increase in number of days with more than 75% humidity and more rainy days; coupled with

temperature range of 12°C–32°C mycotoxin concentrations in grains tend to go up (Schaafsma & Hooker, 2007).

Fusarium culmorum and *Microdochium nivale* used to be dominant causing FHB, in wheat under cool and temperate weather conditions, however *F. graminearum* has become prevalent in the recent years in Northern Germany (Miedaner et al., 2008), England and Wales (Jennings et al., 2004), and the Netherlands (Waalwijk et al., 2003). Since *F. graminearum* produces higher amounts of mycotoxin compared to *F. culmorum* and *M. nivale* being nontoxigenic, such shifts in population dynamics will eventually result in higher concentrations of mycotoxin. Similarly (Ward et al., 2008) reported that in Canada less toxigenic chemotype of *F. graminearum* (15ADON) has been replaced by another chemotype “3ADON,” which also has better ecological fitness. Due to climate change, in the selected locations of Argentina, Brazil, and Uruguay, the risk of FHB has been projected to be higher than at any specific time period during the last 30 years for all except single location (Fernandes et al., 2004). The biggest risk from FHB arises from the projected increase in the number of rainy days, which coincides with the critical growth stages of wheat during the September to November months. These predictions mainly consider changes in climatic variables but does not accommodate increase in the concentrations of CO₂, O₃, etc. (Tiedemann & Firsching, 2000).

Raising CO₂ levels in the atmosphere can directly intensify the severity of FHB and crown rot. Under higher CO₂ concentrations, an increase in *Fusarium* biomass per unit wheat tissue has been reported. This can consequently increase inoculum load of *Fusarium* among consecutive seasons as well as there are chances that under higher CO₂ concentrations breakdown of resistance against *Fusarium* may happen in wheat varieties having moderate resistance (Mellor et al., 2010). In addition, projected increase in crop biomass by 17% due to the increase in CO₂ concentrations (Ainsworth & Long, 2005) will also enhance the pathogenic load in stubble, straw, and agricultural wastes. Similarly, in barley also, FHB has been deleteriously affecting brewing quality of grains, leading to significant concerns in brewing and malting industries (Schwartz, 2003).

12.6 Impact of climate change on the pest and disease management using chemicals

Global warming can potentially affect the efficacy of disease and pest management using chemicals by (1) altering temperature regime and rainfall pattern, (2) bringing out physiological and morphological changes in host plants, (3) changing resistance to chemicals and ecological fitness of pest/pathogen, etc. (Coakley et al., 1999). If rainfall intensity increases, pesticide wash-off from plants is bound to increase ultimately reducing pesticide efficacy. At the same time, the augmented thickness of epicuticular wax layer under enhanced CO₂ can lead to a much-diminished uptake by plants, while wider canopy may hamper proper spray and result in lower concentration of active ingredient in the host plants. To give an example, under higher CO₂ concentrations, the efficacy of pesticide triazophos against *N. lugens* has been found

to be reduced (Ge et al., 2013). On the contrary, there are also chances that higher metabolic rate and evapotranspiration resulting from rise in temperatures can lead to enhanced uptake of plant protectants eventually leading to higher toxicity to insects. Similarly, there are also reports that variations in daily temperatures can result in higher toxicity of a pesticide (Verheyen & Stoks, 2019) which will be advantageous in reducing pesticide requirement under climate change scenario.

In experiments simulating enhanced CO₂ and higher temperatures fungicides azoxystrobin and mancozeb showed improved efficacy against *Phoma* leaf spot caused *Phoma betae* (Gilardi et al., 2016). Use of pesticides may go up if changes in physiology of plants restricts uptake and translocation of active ingredients or climatic events like intense rainfalls increase the washing off. Furthermore, this will also necessitate repeated applications. Thus, the application methods and application rates of plant protectants should be modified to cope up with the new challenges. Formulations based on granules may be better for applications as they are comparatively less affected by washing off.

12.7 Impact of climate change on weeds

Many weeds act as collateral/alternate hosts of diseases and pests and play crucial role in their survival. Just like crops weeds are also affected by climate change. However, weeds have several preadaptations at the biochemical, molecular, or at whole plant level to cope up with climate change and most probably better than crops in doing so. Higher CO₂ concentrations can promote growth and carbon assimilation in weeds also. Similarly, they may also benefit from improved genetic variations, ecological fitness, physiological plasticity, etc. reaping more advantages from climate change compared to crops. Global warming may also convert sleeper weeds to invasive ones.

Problematic weeds that are currently restricted to lower latitudes may extend to higher latitudes due to global warming. According to (Patterson, 1995) Itchgrass (*Rottboellia cochinchinensis*) an invasive weed could move to central Midwest and California with a 3°C heating. Recurrent storms also provide chances to invade new regions. Changes in CO₂ concentration in the atmosphere and presence of “greenhouse gases” may exert direct physiological as well as indirect effects on weed–crop interactions and influence management measures against weeds (Patterson, 1995). Stress from climatic factors like temperature, water, and light as well as the availability of nutrients will also affect interactions among weeds and crops. Further, due to such stress, crops may become more susceptible to diseases and pests and can become less competitive against weeds.

Like crops, weeds having different photosynthetic pathways (C₃ or C₄) are most likely to respond in different ways to climate change. At the global level, many of the worst weeds belong to the C₄ pathway. It is anticipated that C₃ weeds get more advantages from elevated CO₂ compared to C₄ weeds, hence damages from C₃ weeds might increase. However, during drought C₄ weeds will have more advantages over C₃ crops under higher CO₂ concentrations. Higher CO₂ concentrations under

adequate water increases C_3 weed competitiveness in C_4 crop plants. C_3 weed *Taraxacum officinale* (Dandelion) formed more fertile seeds and robust seedlings under higher CO_2 concentrations. Also seeds from plants growing under elevated CO_2 were considerably heavier with higher germination percentage, forming larger seedlings which helped in early establishment in the next generation. Besides, at seed maturity, achenes had characters like higher stalks, longer beaks etc. which would aid in dispersal of seeds by wind to far reached areas. Dandelion has characteristics such as adaptations to disturbance along with high competitiveness, that enhances its reproductive and vegetative potential under elevated CO_2 conditions (McPeck & Wang, 2007). This suggests that weeds like Dandelion will become much more problematic in the future due to climate change. Further, drought tolerant weeds will also become more aggressive due to decrease in rainfalls in many regions.

The management of weeds using herbicides might become more challenging with rising CO_2 and changing climate as variations in the rainfall pattern, temperature, humidity, and water availability as well as wind would affect the efficacy of herbicides. Luxuriant growth will also reduce the efficacy of herbicide due to the dilution effect, making the management of weeds tougher and much more expensive (Patterson, 1995). Because of changes at morphological, physiological and anatomical levels such as thicker leaves, reduced number stomata and conductance, the uptake of herbicide also get reduced limiting the efficacy. Glyphosate is less effective under higher temperatures against *Conyza canadensis* (Kleinman et al., 2016) and under elevated CO_2 levels against weeds like *Chenopodium album*, *Cirsium arvense* (Ziska et al., 1999, 2004), and weed populations in Soybean (Ziska & Goins, 2006). Similar results were also reported by (Matzrafi et al., 2019) against *C. album* and *Conyza canadensis* under higher temperature, elevated CO_2 concentrations, and under the combination of both also.

12.8 Plant protection under the changing climate

Challenges are many in agriculture, as we look forward to ensure food for ever-growing population under changing climate and dependency on plant protectants will grow even more. Changes in global as well as local climate can affect the efficiency of various management strategies in numerous ways like the decreasing efficacy of chemicals, making biocontrol agents more vulnerable, increasing risk of movement of aggressive pest/pathogen species, breaking down the host resistance, etc. This may be due to the (1) variations in temperature, precipitation and wind pattern, and (2) changes in the morphology and physiology of crop plants (Coakley et al., 1999). Furthermore, strategies like adjusting or delaying sowing dates may become less effective and decision-making will become much for cumbersome due to mounting uncertainties. The relative efficiency of many of the pest and disease management options like host resistance, biocontrol agents, biopesticides, and synthetic chemicals will probably change because of climate change. For sustaining agriculture production, pest and disease management strategies should invariably ensure efficiency under climate change scenario. Recognizing key constraints in present approaches

and understanding how to improve pest and disease management strategies can enhance global food security. Mitigating climate change by devising novel management tactics is also essential for sustaining and improving the production levels.

Extensive cultivation of a single variety having resistance will hasten the chances of resistance breakdown (Pangga et al., 2011), whereas mixed communities promote considerable stability (Huang et al., 1994). Hence, strategies for greater resilience in farming should envisage higher genetic variability, both within and among cultivars, thereby establishing a broad genetic base for resistance against biotic and abiotic stresses. Therefore, adopting polygenic resistance, preferably effective against a number of target pests and diseases, as well as having robust expression under a broad range of CO₂ concentrations and temperatures, may offer long lasting protection. Nonetheless identifying and transferring such resistance will not be an easy task.

Humans have been continuously selecting genotypes to suit objectives like having bigger fruits or larger grains which results in change of developmental cycle to improve the productivity, which makes assimilate-remobilization phase more susceptible attack from diseases and pests (Newton, Fitt, et al., 2010). This leads to the loss of yield-loss buffering (the ability to sustain of yield in spite of the pest or disease attack), a concept that has not been able to attract required attention as a target in breeding programs (Bingham & Newton, 2009). This stage is also likely to overlap with down-regulation of host defense pathways as they are no longer required to be activated, since senescence and seed dispersal are about to start. We should aim to breed and achieve some level of “ecological tolerance,” as it is better to have manageable levels of infections and infestations that cause acceptable yield loss, rather than trying to eradicate pathogens and pests completely (Newton et al., 2010b). The selection of a crop for cultivation is based on several factors and climate is one among them. Other factors like end-user demand, better price, availability of skilled labor, etc. can push such climate boundaries with the help of breeding and production strategies such as cultivating under glass houses, use of hydroponics etc. As the climate is changing with more unpredictable weather events (Pachauri & Reisinger, 2007), it is possible that farming of a crop may move from high-risk-prone areas to low-risk-prone areas. Thus, crop distributions will change geographically. Though, this will happen only not because of global warming but also, due to other limitations like inadequate water supply, salinity and depletion of soil nutrients.

Pest infestations and the occurrence of diseases are influenced by complex changes in crops and farming practices that may result from changing climate. To evade the outbreaks of pests and diseases in the future preemptive adaptation is required which comprises breeding for suitable resistance and ensuring its longevity by various means. This also involves proper monitoring, early detection, limiting inoculum and preventing spread. Fundamentally, this defines functional diversity (how organisms in an ecosystem function and operate) at a range of scales (Newton et al., 2009). As functional diversity is intricate at all scales, adaptation strategies to climate change must also similarly complex.

Polycymakers should also account for the impact of climate change while devising IPM strategies. Foremost, monitoring should be strengthened to have more precise

data estimates on economic threshold levels. Care should be taken to develop a strong spatiotemporal monitoring network with fine-scale monitoring of diseases and pests, on the basis of available surveys in the field for detecting frequently undermined effects of climate change and higher temperatures. Similarly, both day and night time monitoring needs to be undertaken for identifying possible impacts of night warming as stated above. The necessity for a well-coordinated surveillance system supported by robust diagnostic networks and easily accessible information systems is the need of the hour. However, expenses involved in such magnanimous efforts can be prohibitive for most of the developing countries. For instance, the Centre for Agriculture and Biosciences (CABI) is devising a Global Plant Clinic (GPC) network wherein “plant doctors” provide immediate diagnoses and health advice and also has expertise and resources for more challenging diagnoses. It can also supply quality-controlled data for a community surveillance system, enabling early detection of new pathogens or pests and providing information and research at local as well as worldwide as it is facilitated by a well-integrated organization at the global level. Various agencies of different types should collaborate with each other, combining, expertise, knowledge and devising strategies in unique ways for common good. Developing long-term decision support systems should be given priority accommodating possible future changes in the climate. This should encompass a wider vision, from fundamental knowledge on pathogen populations, resistance, distribution of location specific cultivars etc. Efforts such as the Borlaug Global Rust Initiative, addressing the impacts of climate change on a specific disease at global level with a possible direct effect on food security is one such example.

Due to global warming, secondary or minor pests and pathogens can also become much more problematic. Hence apart from regular pests, monitoring of minor pests as well as invasive pests must be reinforced to minimize losses from their unforeseen outbreaks. Further making changes in planting systems by increasing the temporal and spatial diversity will be also helpful in reducing the ill effects of climate change to a great extent. This is required because of the uncertainties about the exact route of climate change and the frequency with which events like extreme heat waves will happen. Approaches like intercropping on the basis of push-pull concept (raising plants around a crop that repel pests while maintaining plants which attract and trap pests some distance away from the main crop) or shifting the cultivation of genotypes that are at present adapted to southern parts to more northern latitudes to cope up with the heating tendencies will be also useful. Diversification is a tactic proposed in other fields like forestry (Hof et al., 2017) to achieve more resilience. While evolving varieties resistant to diseases and pests, desirable traits of wild relatives to cope up with extreme weather conditions should be integrated keeping an equilibrium between the resistance to disease/pest and resistance to extreme climatic events; eventually finding the ideal blend of various resistance genes to maximize the yields. Also, biological control agents that are better adapted or resistant to extreme weather should also be utilized at suitable time to fit with phenological synchronization for increasing their efficiency especially under unfavorable weather.

Using a single major gene providing effective resistance under varied climatic conditions is comparatively efficient for a limited target pest or pathogen; however,

this is highly vulnerable and does not last for long. Efficacy can be further augmented by integrating heterogeneity into both the crop as well as risk management processes, successfully distributing the risk, although at the cost of deriving maximum profit from exploiting less durable choices like widespread application of a single plant protectant or extensive monocultivation of resistant cultivar (Newton et al., 2009). For biotrophs like rust which follow “gene-for-gene” model of host-pathogen specificity, more reliable management can be derived from combining different resistance genes, assembled by MAS (marker-assisted selection) or other biotechnological tools. Biotechnology can be successfully used for identifying new genes (tolerance to drought, salinity, high temperature), transferring of genes defying species barrier, over expression of genes within species, modification of fatty acid unsaturation (enhances chilling tolerance improving the fluidity of cell membrane and reduces chilling-induced membrane rigidification), increasing the production of osmolytes, etc.

Upon developing, resistance should be assessed using facilities that can mimic future climatic events which includes higher temperatures (Huang et al., 2006) to estimate their durability and endurance. Considering the possibilities that may occur in future; preemptive breeding can also be initiated in such facilities to recognize and substitute the most vulnerable genes or combinations of genes. Meanwhile controlled experiments can be conducted to assess the impacts of diseases and pests, simulating possible future climatic situations. Such researches should focus on finding out interactions among a number of global change drivers rather than concentrating on effect of a single factor. These studies can guide policy makers to identify of major challenges for future investments. The use of various financial tools like crop insurance as buffer for shielding farmers from increased vulnerability, can bring stability in farming sector.

An increase in biomass of crops as well as alternate hosts due to the climate change, will further enhance production of inoculum particularly in case of necrotrophs. Under such circumstances combining partial resistance with agronomic practices and other available options to evolve robust integrated crop protection tactics will be quite useful. Understanding on biology of the pathogen and epidemiology in agriculture systems must advance considerably to accommodate changes in geographical distribution of crops and pathogens, for effective management of necrotrophic pathogens under climate change. As cultivation shifts to suit climate, there will be changes in breeding targets due to deviations in disease dynamics, pathogen spectra and relative economics (Ortiz et al., 2008). Quicker plant growth due to rising temperature can increase the necessity of pesticide applications. Nonetheless, developing resistant cultivars is healthy, economical and ecofriendly, as evident from the use of Bt-cotton in countries like China (Huang et al., 2003) and India. At last, while recommending plant protectants local climate regimes need to be kept in mind to improve the overall efficiency and for minimizing the requirement of active ingredients.

12.9 Mitigation strategies

Embracing measures to minimize the release of greenhouse gases will help us to mitigate global warming to great extent. When it comes to the agriculture use of fossil

fuels for various activities like pest management should be brought down. Industrial production of fertilizers and agrochemicals, their transportation and spraying needs considerable amount of energy and by reducing the pesticide use, release of greenhouse gases can also be reduced. Synthetic chemicals should be judiciously applied while adopting more sustainable options like green manuring, green leaf manuring, vermicomposting, the use of biocontrol agents, etc. Transplanted rice is one of the major sources of methane from agriculture along with dairy cattle. Continuous flooding of rice fields leads to the emission of methane, an important greenhouse gas and it also aggravates problem of plant hoppers on the crop. Likewise, the excess use of nitrogenous fertilizers stimulates pest attack and is also responsible for nitrous oxide emission. Therefore, alternate wetting and drying can be adopted which reduces methane emission and also reduces plant hopper incidence on the crop. Gradual shifting to millets will also help in long term as they require less water and are better adapted to adverse climate. Controlled experiments can be used to compare the disease/pest incidence under simulated current and future climatic conditions. Rather than elucidating the response functions of biological processes, such experiments should focus on examining interactions among multiple global change drivers.

12.9.1 Surveillance and monitoring

The central aspect of monitoring under climate change scenario is early detection of invasive species. The familiar effects of invasive species on ecosystem comprises loss of threatened and endangered species, changes in composition and structure of terrestrial as well as aquatic communities and decrease in species diversity as a whole.

12.9.2 Detection of changes in geographical distribution

Climate change is projected to alter distribution of pests and pathogens; thus, it becomes vital to detect the changes in geographical distribution of various species. Generic modeling tools like CLIMEX and BioSim have already established their worth in such studies.

12.9.3 Forecasting and forewarning

Reliable medium-range weather forecasts can be helpful in proper timing and decision making of agricultural operations like sowing, application of fertilizers and plant protectants, irrigation, harvesting and storage. This will enhance the agriculture production and the efficiency of crop protection. Similarly, forecasting of pests and diseases can caution stakeholders about the imminent situation and to adopt preventive measures.

12.9.4 Pest management options

IPM mainly comprises of host resistance, cultural operations, biological control agents, and chemicals. Their efficacy will be affected by the changes in climate and

thus would require suitable alterations and modifications for sustaining their efficiency.

12.9.4.1 Biological management

Biodiversity is critical for maintaining abundance of natural enemies and antagonists. Hence enhancing functional diversity in agro-ecosystems is necessary to improve the resilience and minimize yield losses due to diseases and pests. Biocontrol agents like *Beauveria bassiana*, *Metarhizium anisopliae*, NPV (Nuclear Polyhedrosis Virus), Cytoplasmic Polyhedrosis Virus (CPV) and Bt (*Bacillus thuringiensis*) offers great opportunities. As they are specific and eco-friendly, microbial biocontrol agents will be ideal choice for integrated pest management under climate change.

12.9.4.2 Cultural management

Due to the ongoing climate change sowing dates of different crops will need adjustments, that may also change host-pest synchrony. Hence it will be essential to find out changes in pest-host interactions under various agronomic practices. Pests like *Bemisia tabaci* and *Helicoverpa armigera* infests cotton late in the season and by planting till the middle of May, cotton can avoid damages from them to a great extent. Same technique can be adopted to reduce losses due to *H. armigera* in Bengal gram in Northern parts of India, Brown plant hopper infestation in paddy and mustard aphid in Brassica.

12.9.4.3 Chemical management

Reliable forewarnings will be useful in predicting imminent rainfalls which will in avoid washing off and wastage of chemicals. Similarly, monitoring at regular intervals can aid in taking management measures reducing the overall requirement of active ingredients. Applications at right time, matching with hatching of eggs is more efficient than many untimely applications. Proper application method and placement is also vital to achieve a maximum efficiency.

12.10 Way forward

Changing climate is definitely a threat to farming and global food security, and thus it is inevitable to include crops, pathogens and pests as well as their multitrophic interactions in climate change studies to minimize losses. Though there are number of studies on this issue, it is still difficult to predict how global warming and related changes in climate will impact agriculture ecosystem and eventually affect agricultural productivity. To address this issue, future researches may concentrate on lab experiments under controlled conditions simulating upcoming changes, develop models, conduct field experiments, working out better tactics integrating various effective options.

First of all, when it comes to laboratory experiments and models, our present understanding is inadequate on the impact of extreme climatic events across spatial

and temporal scales. Overlooking aspects like daily maximum and minimum temperatures, and time lapse among each of the extreme climatic events can lead to significant errors in model predictions on the specific biochemical and physiological responses involving plants, pests and diseases to changing climate (Ma et al., 2021a). Consequently, future studies need to examine the effects of ecological relevance of extreme events on crops, pathogens, and insect pests in detail, under laboratory set up. Second findings of present controlled field practices have been found to be inadequate to represent the intricate real-world conditions (Trębicki et al., 2017). Similarly, results from studies conducted at regional or local levels have also failed to be accurate when be extrapolated to larger scales. Hence, there is necessity for additional, broad-scale and long-term researches to achieve realistic field conditions spanning a range of latitude and altitude gradients.

Third, multitrophic interactions in an agroecosystem is intricate, highly delicate and sensitive to various IPM components. There are large voids in our understanding on the effect of various cultural practices, like altering sowing dates, intercropping, application of synthetic chemicals, on disease and pests as well as their interaction with plants. The collective effect of IPM strategies and multiple climatic stresses on crop productivity, pests and diseases; and their interactions is largely unknown. Cross-tolerance might occur while facing a number of stresses, which implies that enhanced to resistance to one stress can also aid in tolerating some other stress, or reciprocally. Therefore, studies are required to address the complex challenges evoked by multiple factors to find out the attainable efficiency of IPM.

Detailed estimates of climate change for given locations are unlikely to be accurate as well as the operations that relies on them. Crop yield-loss models, mostly the results of the often-intricate biological process and interactions among them, must be incorporated in crop growth models, and the same trend values need to be utilized to parameterize both (Butterworth et al., 2010; Evans et al., 2008; Fitt et al., 2011; Gregory et al., 2009). Nevertheless, impact of tolerance to infestation or infection, an area often not addressed in assessment of yield loss, is also required to be included and calibrated under climate change events by experiments (Newton et al., 2010).

Under the climate change scenario, the contribution of improved technologies will be also crucial. Technology interventions are required at production, processing, transportation, distribution and marketing levels to provide sufficient safe and nutritious food, without disturbing the sustainability of the natural environment. Scientists regularly develop and deploy strategies and tactics on the basis of well-established principles to manage pest and diseases, many of which are also valid under climate change when predicted courses, changes and interactions are well accommodated. Studies to enhance adaptive capacity of crops by increasing their resilience to diseases may not include entirely novel approaches, though they may provide additional gain of mitigating increasing CO₂ concentrations (Mahmuti et al., 2009). Hence, it is required to hasten the progress of existing and novel tactics and approaches for achieving effective crop protection. Such investment models should guarantee that management measures span broader range of qualms linked with changing climate.

Furthermore, much information has been assembled on possible impacts of global climate change with the help of models. Preliminary assessments are now accessible for some countries, locations, crops and specific diseases. Now importance must shift from assessing impacts to evolving mitigation and adaptation strategies. Researches on two wide areas of will be crucial under climate change; first we need to estimate efficacy of presently employed cultural, chemical, physical, and biological management measures which includes resistant cultivars and second to evolve novel tools and strategies accommodating possible future climatic conditions.

12.11 Conclusion

To sum up, under the global warming scenario concentrated researches that include interactions among crops, diseases, pests and farming practices are required for farmers agriculturists, practitioners, scientists, and policymakers to comprehend the impacts of changing climate on agriculture. Once a better picture of how global warming and related climate change will affect pests and diseases is derived, stake holders can develop effective management measures against pests and diseases, minimize the applications of agrochemicals and mitigate ill effects of climate change. As there are considerable uncertainties about the changes in climate, it is arduous task to generalize, but ongoing researches help us to elucidate a trend of how pathogens, pests, crops and interactions among them respond to changing climate. Intensified studies on climate change-related matters can lead to better understanding and thereby help in devising improved management strategies against pathogens and pests in the face of present as well as future climate extremes.

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Climate change and secondary metabolism in plants: resilience to disruption

13

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Climate change is affecting the worldwide sustainability of crop plant systems, posing barriers and avenues for farmer financial stability, markets, and sustainability of food supplies (Wheeler & Von Braun, 2013). Rising global temperatures and carbon dioxide levels over the past six decades paired with severe weather patterns such as an increase in the magnitude and duration of drought episodes, extreme heat waves, cold breaks, and flooded areas are influencing crop yields and changing the geographical ranges of crop farming. The concentration of atmospheric carbon dioxide (CO₂) has attained unprecedented levels during the industrial revolution, with an annual mean level of 416.45 $\mu\text{mol mol}^{-1}$ in 2021 (Qaderi et al., 2023), with a predicted rise to 700 $\mu\text{mol mol}^{-1}$ by the year 2100. Temperatures over land and ocean have increased by 1.59°C and 0.88°C, respectively, due to increases in CO₂ and other greenhouse gases (GHGs). By the end of this century, temperatures are expected to rise by up to 5.7°C under the scenario with extremely high GHG emissions (Qaderi et al., 2023). Since climate change is projected to expose a wider range of crops and trees to stressor combinations, it is critical to

comprehend how various stressors combine to impact plant survival, growth, and output (Zandalinas et al., 2024).

According to Challinor et al. (2016), climate change will probably result in decreased output of cereal crops like rice, maize, and wheat globally. Extreme environmental occurrences have also been recognized to have a negative impact on the entire fauna and flora. Additionally, an estimate (FAO, 2009) states that in order to sustain an additional 2.3 billion people by 2050, food crop yield must rise by 70%. Thus, a major concern in the twenty-first century is achieving this goal in the face of severe ecological disasters. Plants have to rapidly modify their physiological and metabolic responses to counteract the impacts of stress and synthesize SMs to establish a new state of equilibrium (Dixon & Dickinson, 2024). High chemical and structural diversity characterize plant secondary molecules, also known as SMs, which can be either volatile or nonvolatile. With an estimated 200,000 different molecules, plant SMs exhibit a remarkable degree of chemical diversity (Holopainen et al., 2018). The three most varied classes of SMs found in higher plants are phenolic compounds (8000), alkaloids (21,000), and terpenoids (around 30,000 identified compounds) (Lämke & Unsicker, 2018). The primary factors driving the diversity of plant SMs are thought to be herbivore pressure and plant chemical defense, which account for the bulk of plant SMs (Lämke & Unsicker, 2018).

Plant SMs play a vital role in human society, being crucial compounds found in nutraceuticals, pharmaceuticals, antioxidants, anti-inflammatory agents, food preservatives, flavor enhancers, cosmetics, and aromatherapy products, etc. (Jamloki et al., 2021). In addition to seasonal and diurnal cycles, variations in climate also affect SM concentrations (Holopainen et al., 2018). SMs are produced by a significant carbon contribution and are then stored in internal organs (lactifers, resin ducts, or vacuoles) or specialized structures (trichomes) (Becker & Kläring, 2016). Younger leaves are more nutrient-dense and have a stronger defense mechanism against biotic and abiotic stressors, furthermore, they also tend to collect metabolites more quickly than older leaves. In recent years, there has been a growing interest in the relationship between the elements of climate change and modifications to plant secondary metabolism (Reardon & Qaderi, 2017). Because plant metabolism is so sensitive, research on secondary metabolism frequently produces contradictory findings because even minor environmental changes can have a big impact on metabolic pathways and chemical formation. Understanding the resilience and adaptability of plants to changes in this diverse climate is crucial for food security and ecosystem stability. A number of abiotic stress factors such as heat, salt, and drought affect the growth productivity and survival potential of a plant. This offers valuable leads for scientists to increase crop tolerance; and also boosts agricultural sustainability against climate change. Moreover, this data help to maintain ecosystem services and biodiversity which are responsible for human and environmental health.

13.1 Understanding secondary metabolism in plants

Compounds known as primary metabolites are vital to physiological processes in living things. Consequently, these metabolites are typically present in every type of

plant and play a direct function in growth, development, and reproduction. Among the many organic substances, they include protein, lipids, carbohydrates, and nucleic acids all of these being essential for physiological functions (Salam et al., 2023). Alternatively, these metabolites serve as fundamental building blocks for the synthesis of large molecules and offer the necessary energies needed to grow plants and vitality (Shiade et al., 2024). This underscores their importance not only in the survival of plants but also in their ability to thrive and adapt in various environments, highlighting their role in overall plant health and productivity. In contrast to primary metabolites, SMs have more specific functions, as they are not directly involved in the growth, development, and reproduction of organisms. Typically, these compounds are unique to particular species and may become unnecessary in various contexts (Böttger et al., 2018). Plants that grow in natural field conditions are continually subjected to a range of abiotic and biotic stressors, including drought, soil alkalinity, salinity, ultraviolet (UV) radiation, extreme temperatures, and pathogen infections, which may have a negative impact on their development and general output (Ahlawat et al., 2024). Additionally, SMs are responsible for producing a variety of compounds that play critical roles in numerous biophysical and biochemical mechanisms in plant tissues and cells.

The continuous sustainability of plants is largely dependent on SMs (Elshafie et al., 2023). The plants have an extraordinary capability to produce a vast array of SMs, including around 40,000 terpenoids, 12,000 alkaloids, and 8000 phenylpropanoids. Additionally, SMs display multipurpose traits that fulfill a variety of roles within plants. One significant function is their use as defense mechanisms and taxonomic indicators, supporting the classification and distinction of plant species, genera, and families (Elshafie et al., 2023). SMs can be categorized into three primary groups: phenolics, terpenes, and compounds containing sulfur and nitrogen. Phenolic compounds, which include lignin, tannins, flavonoids, isoflavonoids, anthocyanins, and coumarins are the most abundant and important class of SMs found in plants. Throughout the plant life cycle, these substances are physiologically essential for improving resistance and adaptability in less-than-ideal circumstances (Saltveit, 2017).

Additionally, phenylalanine is the main substrate for the phenylpropanoid pathway, which is how all of these compounds are produced in plants and greatly aid in their defense mechanisms against a variety of environmental stressors (Dong & Lin, 2021). The phenylpropanoid pathway is influenced by biotic and abiotic variables, such as trace metals (TMs), drought and salinity stress, extreme temperatures, physical injury, pathogen attacks, herbicide applications, nutrient deficiencies, and UV radiation, all of which lead to the accumulation of various phenolic compounds (Valifard et al., 2015). As a result, the build-up of phenolic compounds in plant tissues is regarded as a vital survival strategy for plants in challenging environmental conditions. Flavonoids, isoflavonoids, and anthocyanins are essential for plant defense and are synthesized in response to a variety of environmental stresses. The antioxidant qualities of flavonoids in particular provide protection, particularly when plants are exposed to water constraints (Li et al., 2021a, 2021b).

Additionally, it was shown by Nakabayashi et al. (2014) that flavonoids greatly increase *Arabidopsis thaliana*'s tolerance to water scarcity.

In the herbal medicinal plant *Hypericum brasiliense*, levels of the flavonoids quercetin and rutin were found to rise under stress circumstances including drought and waterlogging, whereas a distinct reaction was observed under cold stress (de Abreu & Mazzafera, 2005). Furthermore, it was found that anthocyanin's, which have antioxidant qualities and can scavenge reactive oxygen species (ROS), increased their content in plant tissues in response to both drought and cold stress, protecting plant cells (Xiang et al., 2021). Anthocyanin levels significantly increased in cultures of red-fleshed apple callus when exposed to low temperatures (16°C) (Wang et al., 2016). Additionally, under low-temperature stress, the cell wall produces more phenolic chemicals, which show up as lignin or suberin (Cabane et al., 2012). Moreover, when *Silybum marianum* in vitro cultures are exposed to different abiotic stress treatments, including sodium chloride (NaCl), polyethylene glycol, and gamma irradiation, the flavonolignan silymarin has been observed to accumulate in the cells as a result of the defense mechanisms that cells use to lessen the negative effects of these stressors (Elateeq et al., 2020). In the body, terpenoids such as diterpenoids, gibberellic acid (GA), and sesquiterpenoid abscisic acid (ABA) play an important role as phytohormones in defending against biotic and abiotic stressors. Terpenoids also function as phytoalexins, which are low-molecular-weight antimicrobial substances that plants create as a defensive mechanism against environmental stress. For example, *Oryza sativa* has been found to have a large number of diterpene phytoalexins (Gu et al., 2019).

Similarly, in response to diseases and herbivores, cotton plants produce defense metabolites called sesquiterpenoid phytoalexins like gossypol, hemigossypolone, and heliocides that build up above and below the soil surface (Yang et al., 2013). Additionally, diterpene phytoalexins, such as zealexins, kauralexins, and oryzalexins are produced in the leaves and roots of rice and maize. These phytoalexins have antimicrobial properties and offer defense against harmful fungal diseases like *Magnaporthe grisea*-induced rice blast (Gu et al., 2019). Furthermore, rice accumulates phytoalexins in response to TM stress and UV radiation exposure. Vaughan et al. (2015) claim that the rise in phytoalexin levels in response to drought is unique to the roots and has no effect on the levels of phytoalexin in the plant's aerial parts. According to Massacci et al. (2008), cotton species that are experiencing drought have been found to have lower concentrations of terpenoid chemicals. Yusuf et al. (2010) found that *Brassica juncea*'s high amounts of soluble alcohol tocopherol, which is well-known for its antioxidant qualities, significantly reduce stress by stabilizing cell membranes impacted by osmotic pressure, salt, and TMs. Furthermore, in soybean plants, saponins have been found to be one of the key SMs linked to salt stress tolerance (Wu et al., 2008).

SMs, such as nitrogen-containing secondary chemicals including alkaloids, cyanogenic glycosides, glucosinolates, and nonprotein amino acids are part of the complex defensive system that plants have developed to combat a variety of stresses (Miyagawa, 2009). For instance, poppy plants increase their production of alkaloids during periods of drought and under conditions of salinity stress (Davodnia et al., 2017).

In certain cultivars of lupins (*Lupinus termis*), alkaloid levels were also affected by drought and treatment with activated yeast extract (Taha et al., 2020). Furthermore, glucose and amino acids are converted into cyanogenic glycosides and glucosinolates, which include nitrogen and sulfur. Likewise, Rodziewicz et al. (2014) showed that these natural substances have a major role in plants ability to withstand a variety of biotic and abiotic environmental stresses. According to Mewis et al. (2012), subjecting *Arabidopsis thaliana* to waterlogging and drought raised the plant levels of flavonoids and aliphatic glucosinolates. Furthermore, in *B. juncea*, glucosinolate concentrations were notably higher during the vegetative phase under water-deficit conditions, emphasizing the adaptive role of these metabolites in stress response.

13.2 Impact of climate change on secondary metabolism

13.2.1 Climatic factors

Climate change refers to any notable, long-term change in the typical weather patterns of a region (or the entire planet) over a long period. It is concerned with unusual climate fluctuations and how they affect other regions of the world. These modifications may occur over tens, hundreds or even millions of years (Pant et al., 2018). Higher temperatures, altered precipitation patterns and elevated atmospheric CO₂ concentrations are all examples of climate change scenarios (Pereira et al., 2021). One natural phenomenon that significantly affects Earth's climate is the greenhouse effect. Near the earth's surface, it produces relatively warm and habitable conditions that have facilitated the growth and well-being of humans and other living species. Both natural and anthropogenic activities contribute to the release of GHGs into the atmosphere. One of the main causes of climate change is the release of harmful gases from factories, industries, machinery, and automobiles (Mikhaylov et al., 2020). The rise in GHGs such as carbon dioxide (CO₂), water vapor (H₂O), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF₆), etc., has raised the earth's temperature overall and caused global warming. The troposphere, which is home to life, is where this atmospheric greenhouse effect takes place. Instead of the current average of 14°C, the average temperature on Earth's surface without the greenhouse effect is said to be around -19°C (Haines, 2022). However, the environment is seriously threatened by the continuously changing climate caused by increased human activity, such as urbanization, fast industrialization, deforestation, burning of agricultural waste, excessive use of nonbiodegradable items, etc. The melting of glaciers and an increase in heat waves are just two of the many changes in many ecosystems, weather patterns, and the biosphere brought on by the rise in the average global temperature. Ocean and land temperatures have increased by 0.88°C and 1.59°C, respectively, due to increases in CO₂ and other GHGs (Adak et al., 2023). By the end of this century, temperatures are expected to rise by up to 5.7°C under the scenario of exceptionally high GHG emissions.

Earth's temperature has risen by 1.2°C since the industrial age, according to the Intergovernmental Panel on Climate Change. The effects are currently visible in many ecosystems around the world, even though this may not seem like much. Higher temperatures can cause evapotranspiration to occur more quickly, altering hydrological cycles and reducing the quantity of water that plants can absorb. Due to a variety of factors, including heat waves, droughts, and unpredictable precipitation, most ecosystems are now far more susceptible to disturbances of any kind (Ummenhofer & Meehl, 2017).

The amount of CO₂ in the atmosphere has risen to a record high since the Industrial Revolution. The yearly average concentration was 416.45 $\mu\text{mol mol}^{-1}$ in 2021 and is predicted to rise to 700 $\mu\text{mol mol}^{-1}$ by 2100 (Qaderi et al., 2023). Despite being essential for photosynthesis, too much CO₂ affects the normal equilibrium processes in plant systems. Plants often develop more quickly when exposed to high CO₂ concentrations and their tissues have a higher carbon-to-nitrogen ratio than other tissues, which alters metabolic pathways and lowers nutritional quality (Gamage et al., 2018).

Plant communities are harmed by extreme weather events like hurricanes, floods, and wildfires that are made worse by climate change. Drought-stressed plants grow more slowly, struggle with photosynthetic processes, and are more vulnerable to diseases and pests. Storms, floods, and cold waves are among the extreme weather occurrences that are occurring increasingly frequently over the world. These disturbances affect not only vulnerable ecosystems but also the displacement of plants from niches that they otherwise could have held in stable climates typical for those plants to thrive. Climate change-mediated variability in temperature, precipitation, and CO₂ levels has far-reaching impacts on plant physiology; however, less is known about its potential consequences for biochemical interactions (Reid et al., 2019). These environmental transformations push plants to adopt physiological and metabolic changes. More broadly, anthropogenic climate change continues to outpace the adaptive capacity of many plant species and as a result, is causing changes in growth, development, and metabolism (Thuiller et al., 2008). Biosynthetic pathways of key SMs are currently seriously altered due to the factors of climate change and stress which include phenolic compounds, alkaloids, flavonoids, and terpenoids (Zandalinas et al., 2022). The scope and manner of such changes are highly variable between species and depend on the particular stress that different individual plants might face. Yet, general trends appear to show up in a variety of environmental changes, frequently leading to significant shifts in the structural diversity and concentration of these metabolites. Considering the complex relationship between environmental stress and plant biochemical pathways, such alterations, as adaptive reactions, have significant implications for sustainable ecology and agronomy (Islam et al., 2021).

13.2.2 Effect of climate change on secondary metabolism

Climate change has a profound impact on plant life, influencing various physiological and metabolic processes. Among the most significant effects is its impact on secondary

metabolism, which plays a crucial role in plant defense, growth, and adaptation to environmental stressors. As climate change alters temperature, precipitation patterns, and atmospheric composition, these shifts can either suppress or enhance the production of SMs such as phenolics, terpenes, and alkaloids (Table 13.1).

13.2.2.1 *Effect of temperature*

It has been expected that temperature increases are proven to impact crop yields, high temperatures can reduce net photosynthesis, cause observable damages such as leaf senescence and blistering, and increase transpiration (Qaderi et al., 2006). High temperatures can interfere with vital life processes such as flowering and germination and also cause risk to food security (Ohama et al., 2017). High temperature may decrease potato yields by 18%–32%, short time heat stress may cause male sterility in Arabidopsis and barley which is reported by many research (Bahuguna & Jagadish, 2015). Plants detect temperature changes by cellular thermosensors, which stimulate the activation of heat shock transcription factors (HsfA1s), which are important for heat stress reactions (Ohama et al., 2017). On the other hand, growth, and distribution are negatively impacted by cold stress, which occurs beyond 20°C or freezing and leads to losses (Kaplan et al., 2004). Temperature moves causes cellular responses, membrane instability, causing protein denaturation, downregulated energy metabolism, favoring protective compound accumulation (Zobayed et al., 2005). Rapid metabolic responses, taking place within 30 minutes of being exposed, may shift carbon from growth to defense, limiting yield (Kaplan et al., 2004). Temperature stress also enhances toxic ROS production and also lipid peroxidation signaling oxidative damage (Shohael et al., 2006). Temperature tolerance depends on suitable substances which include protective SMs and hormones. Many research in Arabidopsis show many responses like 4% responded to heat only, 31% of metabolic were unaffected 38% to cold stress and 19% shows both heat and cold stress, demonstrating different pathways for high temperature and cold stress responses (Kaplan et al., 2004). Temperature also influences SM synthesis in plants; while higher temperatures generally increase metabolite production, they may reduce monoterpene content in certain species, such as Douglas fir (Qaderi et al., 2023).

13.2.2.2 *Effect of CO₂*

Excessive CO₂ level affect the chemical composition of SMs of plant, reducing nitrogen content in grain, seed, and vegetative parts, which decreases protein levels (Idso & Idso, 2000). It was shown that increased CO₂ level enhance phenolic compounds and reduce tannins in leaves and change monoterpene amount and improve the total concentration of phenolic in conifers. Specifically, high CO₂ concentration improves α -pinene levels and reduces the β -pinene levels in needles (Srivastava et al., 2021).

13.2.2.3 *Effect of drought stress*

Drought stress caused by a reduction in water availability either through increased evaporation or low precipitation, which frequently decreases plant development and productivity (Amiri et al., 2015; Kleinwächter & Selmar, 2015). Although agriculture utilizes more than 70% of the global water supply, modification to water accessibility

Table 13.1 Effect of different climatic factors on secondary metabolites in plants.

Salt			
Plant	Secondary metabolites	Response	References
<i>Grevillea</i>	Anthocyanin	Increased	Kennedy and De Filippis (1999)
<i>Lycopersicum esculentum</i>	Sorbitol	Increased	Tari et al. (2010)
<i>Oryza sativa</i>	Proline	Increased	Chi Lin et al. (2002)
<i>Sesamum indicum</i>	Gamma-aminobutyric acid	Increased	Bor et al. (2009)
<i>Triticum aestivum</i>	Proline and soluble sugar	Increased	Khatkar and Kuhad (2000)
<i>Vitis vinifera</i>	Proline	Increased	Singh et al. (2000)
Drought			
<i>Cakile maritime</i> cvs Jerba and Tabarka	Polyphenol	Increase in Jerba, decreased in Tabarka	Ksouri et al. (2007)
<i>Camellia sinensis</i>	Glucosinolates	Increased	Hernández et al. (2006)
<i>Datura innoxia</i>	Total alkaloid content	Increased	Brachet and Cosson (1986)
<i>Glycine max</i>	Trigonelline (nicotinic acid betaine)	Increased	Cho et al., 1999
<i>H. brasiliense</i>	Betulinic acid		de Abreu and Mazzafera (2005)
<i>Hypericum brasiliense</i>	Rutin		de Abreu and Mazzafera (2005)
<i>Lupinus angustifolius</i>	Chinolizidine	Increased	Christiansen et al. (1997)
<i>Lycopersicum esculentum</i>	Jasmonic acid	Increased	Pedranzani et al. (2007)
<i>Papaver somniferum</i>	Morphine	Increased	Szabó et al. (2003)
<i>Scrophularia ningpoensis</i>	Glycosides	Increased	Wang et al. (2010)

(Continued)

Temperature			
<i>Hypericum perforatum</i>	Hypericin	Increased	Zobayed et al. (2005)
<i>Polygonum minus</i>	Flavonoids	Increased	Gao et al. (2015)
<i>Triticum aestivum</i>	Phenolic acids, flavonoids and phytosterols	Increased	Shamloo et al. (2017)
Elevated CO₂			
<i>Arabidopsis thaliana</i>	Glucosinolates	Decreased	Paudel et al. (2016)
<i>Centella asiatica</i>	Flavonoid	Increased	Siavash Moghaddam et al. (2017)
<i>Hibiscus sabdariffa</i>	Phenolic and Anthocyanins	Increased	Ali et al. (2019)
<i>Hypericum perforatum</i>	Hypericin	Decreased	Sharma et al. (2020)
<i>Paris polyphylla</i> var. <i>yunnanensis</i>	Saponins	Increased	Qiang et al. (2020)
<i>Pfaffia glomerata</i>	Saponins and phytosteroids	Increased	Ferreira et al. (2019)
<i>Stevia rebaudiana</i> Bertoni	Steviol glycosides	Increased	Hussin et al. (2017)
<i>Valeriana jatamansi</i> Jones	Essential oil (patchouli alcohol, bornyl acetate, β -patchoulene, germacrene D)	Increased	Kaundal et al. (2018)
Elevated Ozone			
<i>Capsicum baccatum</i> L. var. <i>Pendulum</i>	Capsaicin and Dihydrocapsaicin	Decreased	Bortolin et al. (2016)
<i>Hypericum perforatum</i>	Total phenols and flavonoid	Increased	Pellegrini et al. (2018)
<i>Melissa officinalis</i>	Total carotenoids	Increased	D'Angiolillo et al. (2015)
<i>Melissa officinalis</i>	Rosmarinic acid	Increased	Tonelli et al. (2015)
<i>Salvia officinalis</i>	Phenols (gallic acid, caffeic acid, rosmarinic acid)	Increased	Pellegrini et al. (2015)
Interactive Factors (HT $\times$ eCO₂)			
<i>Betula pendula</i> Roth	Chlorogenic acid	Decreased	Kuokkanen et al. (2003)
<i>Festuca arundinacea</i>	Nonprotein amino acids	Decreased	Yu et al. (2012)

(Continued)

Table 13.1 (Continued)

Salt			
Plant	Secondary metabolites	Response	References
<i>Gossypium hirsutum</i>	Total phenolics	Increased	Zhang et al. (2017)
<i>Vitis vinifera</i>	Anthocyanins	Decreased	Ayenew et al. (2015)
HT × DS			
<i>Phoenix dactylifera</i>	Isoprene	Increased	Arab et al. (2016)
<i>Pseudotsuga menziesii</i>	Flavonoids	Increased	Jansen et al. (2014)
HL × UVB			
<i>Hydrocotyle leucocephala</i>	Flavonols, quercetin anthocyanins	Increased	Müller et al. (2015)
eCO₂ × LL			
<i>Labisia pumila</i>	Flavonoids, anthocyanins, total phenolics	Increased	Ibrahim et al. (2014)
eCO₂ × UV-B			
<i>Betula pendula</i>	Tannins, total phenolics	Increased	Lavola et al. (2003)
UVB × BL			
<i>Lactuca sativa</i>	Phenylpropanoids	Increased	Ebisawa et al. (2008)
HT × HL			
<i>Phragmites australis</i>	Isoprene	Increased	Velikova and Loreto (2005)
HL × DS			
<i>Xerophyta humilis</i>	Zeaxanthin	Increased	Beckett et al. (2012)
HT × LP			
<i>Brassica oleracea</i>	Glucosinolates	Increased	Steindal et al. (2015)
HT × aCO₂ × DS			
<i>Arabidopsis thaliana</i>	Total phenolics	Decreased	Abo Gamar et al. (2019)
LT × eCO₂ × DS			
<i>Arabidopsis thaliana</i>	Total phenolics	Increased	Abo Gamar et al. (2019)

may have significant economic impacts (Kleinwächter & Paulsen, Bloem, et al., 2015). Various species respond differently to drought stress and around more than 30 metabolites are related to water availability (Chan et al., 2013). Through osmotically adapting, collecting substances, and generating more phenolic and terpenoid compounds, plant improve drought stress and enhance drought resistance. While plants that can tolerate drought like cumin and maize tend to possess more phenolic content (Hura et al., 2008; Rebey et al., 2012), plant which are vulnerable to drought such tea and cotton, have lower phenolic content (Cheruiyot et al., 2007; Yildiz-Aktas et al., 2009). Drought stress can enhance in terpenes like monoterpenes in thyme and sesquiterpenes may decrease due to reduced glandular trichomes (Yadav et al., 2014). Carotenoids frequently decline under drought stress, except in a few species like nasturtium (Qaderi et al., 2023). Although extreme drought stress conditions damage photosynthetic structure, plants produce higher xanthophyll pigments to release extra energy to in order to fight against oxidative stress caused by drought stress (Fini et al., 2012). Nitrogen-containing substances like glucosinolate, which rise in stressed crops such as canola and kale are affected by drought stress. Alkaloids also typically increased, with brief rise observed in celandine and other drought tolerant plant (Qaderi et al., 2023). The level of GABA may increase in many plants, although in crops like rice, but found unaffected on wheat polyamine putrescine decreases with long-term drought stress (Bowne et al., 2012; Do et al., 2013).

13.2.2.4 Effect of light

The duration, quality, and intensity of light all impact the development, morphology, and production of SMs via photomorphogenesis, making it essential for plant growth (Fazal et al., 2016; Kopsell et al., 2015). Plants absorb about 90% of blue and red light, which triggers reactions like stomata control, chloroplast activity, and stem shortening (Kopsell et al., 2015). While species-specific light reaction may vary, strong light intensity usually raises terpenoid and phenolic synthesis, enhancing plant defense via antimicrobial activity and ROS scavenging (Ouzounis et al., 2014).

Light quality also impacts metabolic responses, with blue light frequently enhancing flavonoids and other phenolic compounds and red light also enhances p-cumaric acid in ginseng and rosmarinic acid in basil (Park et al., 2013; Shiga et al., 2009). Although, blue light also increases glucosides and glucosinolates, which support stress and defense responses, mainly in sensitive plants, favouring carbon based defense such as phenolic (Kopsell et al., 2015). Terpenes show light-exposure variation, with specific wavelength, like far red and green, regulating storage or concentration in specific species (Park et al., 2013). In general, different light qualities and intensities impact plant adaptation and SMs composition, mainly via molecules that react to stress such as phenolic, nitrogen based metabolites and terpenoids (Qaderi et al., 2023).

13.2.2.5 Effect of ultraviolet-B radiation

The destruction of ozone layers occurs due to CFC and N₂O (Ravishankara et al., 2009) which leads to UV-B radiation (280–320 nm) on Earth about 2%–5% in every decade

across Europe (Eichholz et al., 2012). The UVR8 receptor in plants senses UV-B, which also controls gene expression, growth, and photobiological activities (Kumari & Agrawal, 2010). Flavonoids such as kaempferol and quercetin absorb UV-B and also decreasing ROS and cellular damages (Hectors et al., 2014; Nascimento et al., 2015). Studies reported that UV-B frequently promotes flavonoid and phenolic formation (Qaderi et al., 2023). In a few plants UV-B elevates lignin and tannins, although protein production reduces, and certain phenolic compounds are reallocating (Takshak & Agrawal, 2015). Generally, carotenoids do not change but powerful UV-B can enhance the production of carotenoids (Huché-Théliet et al., 2016; Jansen et al., 2008). Under UV-B radiation nitrogen compounds such as glycosides and alkaloids usually enhance plant defense, but glucosinolates show regular increases. However, few indole alkaloids provide antioxidant properties, alkaloid accumulation, like in tobacco, can be toxic. Temporary defense is facilitated by UV-B-responsive polyamines and GABA (Martínez-Lüscher et al., 2014). This biochemical shift carried on by UV-B shows how the complex way plants have adjusted to greater radiation levels.

13.2.2.6 *Interactive effects of environmental factors*

Abiotic stress like drought stress, high temperature, high light, and high CO₂ have been investigated for their effect on plant SMs (Kleinwächter et al., 2015). These studies reported complex and contradicting effects. High temperature paired with elevated CO₂ raise phenolic content in leaf of cotton and decreases in European aspen, while high temperature and high CO₂ decrease SMs in barley and also decrease chlorogenic acid in silver birch (Mikkelsen et al., 2015). High temperature and drought stress increase the flavonoid and catechin in pine fir, but in berries and grapes anthocyanin production is inhibited by high temperature and high light. Light, temperature, and seasonal variation affect the amount of some chemicals, like glucosinolate, which are highest under mild conditions. Palm and other stressed plant membranes of thylakoid are maintained by isoprene release which is identically influenced by light and temperature. Elevated CO₂ and low light in Kacip Fatimah increase anthocyanins and phenolics via enzyme activity, but high CO₂ and light have the reverse effect on the phenylpropanoid pathway. In addition, blue light or UV-B raises lettuce phenolic pathways. Both light and UV-B stimulate quercetin in Asiatic and Brazilian pennyworts, while high light raises saponins and flavonols. Under drought stress and light carotenoids such as zeaxanthin develop and protect plants from damaging light. Overall creature metabolic pathways and specific surrounding environmental factors all have an important effect on how multiple stresses affect plant SMs (Qaderi et al., 2023).

13.3 Resilience mechanisms: plant adaptations to climate stress

Sessile plants must adapt to climate change disasters or so-called environmental stressors like drought, high temperatures, high CO₂, and salinity, either separately or more frequently combined, in order to live. Catastrophes caused by climate change affect every facet of plant architecture and pose a major obstacle to the development

of sustainable agriculture at a period of rapid population increase. Plants have developed a wide range of molecular programs to sense change quickly and adjust in response to climate change disasters. Plants coordinate and fine-tune their adaptation methods to stress by modifying cellular and molecular activity, growth, and development. The physiological, cellular, and molecular mechanisms behind plants' reactions to environmental stressors have become better understood thanks to significant advancements. Molecular cross-talks, epigenetic modifications, R-gene resistance, systemic acquired resistance, accumulation of plant hormones like salicylic acid, ethylene, jasmonic acid, and ABA, changes in redox status and inorganic ion fluxes, and ROS signaling are some of the main mechanisms underlying climate adaptation and defense (Kissoudis et al., 2014). Physical barriers like the cuticle, stomata, and cell walls play a crucial role in the timely recognition and interception of pathogens. Biochemical investigations have shown that stress-induced processes lead to the accumulation of various metabolites, including nitrogen-rich compounds such as proline, quaternary amino compounds, and polyamines, as well as hydroxyl compounds like sucrose, polyols, and oligosaccharides. Advances in “omics” technologies have revealed that plant responses to stress involve significant alterations in gene expression, resulting in changes to the composition of the plant's transcriptome, proteome, and metabolome (Lamalakshmi Devi et al., 2017). Key mechanisms underlying these responses include metabolic flexibility, interactions between metabolic pathways, epigenetic modifications, and symbiotic relationships (Fig. 13.1).

13.3.1 Physiological and morphological flexibility

Several physiological adaptations have been developed by plants to improve their ability to tolerate stress and persist in challenging circumstances. By boosting their

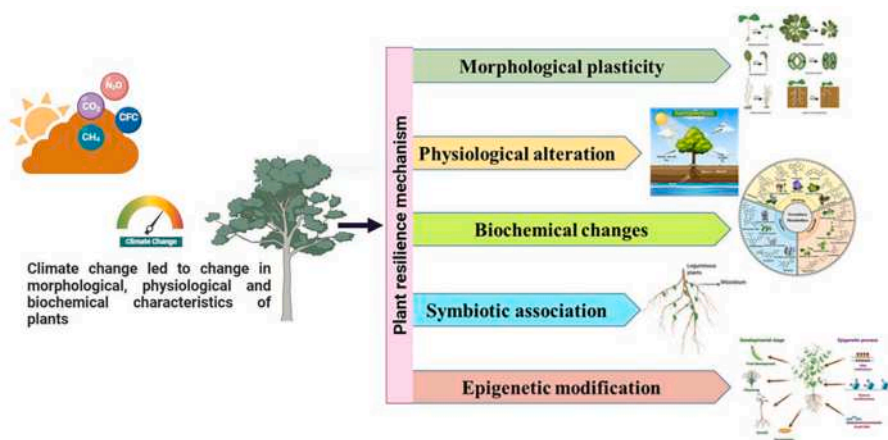


Figure 13.1 Resilience mechanism of plants against climatic stress.

water and carbon utilization strategies, such adaptations encourage plants become more resilient to climate change factors such as the burning of fossil fuels, drought, high temperatures, deforestation, shifting precipitation patterns, elevated atmospheric carbon dioxides (CO₂) concentrations, and restricted resources. With significant implications on plant health and ecosystem resilience, these environmental changes have significant consequences on plant physiological processes, including the rate of photosynthesis, respiration, water balance, blooming and leaf emergence timing, nutrient acquisition, and plant-pollinator interactions (Zaib et al., 2023). The rate of photosynthesis is greatly impacted by variations in temperature and CO₂ concentrations. Due to enhanced enzyme activity, slight to moderate temperature changes can occasionally result in increased photosynthetic rates. However, heat stress imposed through rising temperatures can cause stomata to close, reducing CO₂ uptake and preventing photosynthesis (Way & Yamori, 2014). Under elevated ozone toxicity, the rate of photosynthesis-related to stomatal conductance, osmotic solute, and turgidity of guard cell which is considered to be an adaptive feature to minimize the entry of ozone in plants and also minimized the oxidative stress further strengthened by the reduction in Fv/Fm ratio (Madheshiya et al., 2023, 2024). Several authors reported that the rate of photosynthesis disturbed under elevated ozone concentration which hampered the overall growth and development of plants for which plants stimulate their antioxidant pool to cope with the oxidative stress (Gupta et al., 2024). Rising temperatures have a significant impact on other various physiological and metabolic processes in plants, such as increased evaporation, denaturation of enzymes involved in photosynthesis, higher respiration rates, and affect water availability for plants. The processes of respiration become more rapid; it can result in a net loss of energy for the plant (Atkin & Tjoelker, 2003). Cell turgor pressure and water uptake are maintained during drought stress by the plant's ability to open and close stomata on its leaves to prevent water loss, improve water-use efficiency, and absorb water by adjusting its osmotic potential by accumulating compatible solutes like proline, sugars, and amino acids. The result contributes to avoiding cellular dehydration and damage (Atkin et al., 2005; Flexas et al., 2012). Plants with well-adapted root systems, elongate their existing roots or produce new roots that grow deeper into the soil, increasing branching, development of root hairs, tiny extensions of root cells, and density of root can explore larger soil volumes and the root's surface area, that access water and nutrients more efficiently, and enhance their overall resilience (Ashraf & Harris, 2004; Zhang et al., 2018). Adventitious roots can increase nutrient and water uptake by forming in response to changing environmental conditions, such as flooding or waterlogging. The C4 photosynthetic pathway and crassulacean acid metabolism (CAM) photosynthesis are two prominent examples. Plants become more resilient as a result of these adaptations, which allow them to maximize their carbon and water utilization methods. Succulent plants are primarily adapted to CAM photosynthesis, which minimizes water loss in hot and dry weather. In addition to reducing water loss through transpiration, which improves water-use efficiency, CAM plants open their stomata at night to absorb CO₂. As a photosynthetic adaptation, the C4 pathway increases the efficiency of water usage and CO₂ uptake, increasing a plant's resistance to drought, high temperatures, and low CO₂. In hot, dry

weather, C4 plants can partially cover their stomata, preventing water loss (Sage & Sage, 2009; Zaib et al., 2023). So, plants developing effective adaptation strategies to cope with climate change.

13.3.2 Epigenetic modifications

Plants have complex adaptations, such as epigenetic changes, that give them exceptional resilience to climate stress. These alterations, which include noncoding RNAs, histone modifications, and DNA methylation, enable plants to modify gene expression without modifying their genetic makeup. These systems allow plants to react to environmental stressors like salt, drought, and high temperatures in a dynamic manner. Epigenetic memory frequently facilitates quicker adaptation to stressful situations, improving fitness, and survival. With climate change becoming a greater danger, these adaptive techniques are essential to preserving agricultural output and environmental stability.

13.3.3 Histone modification

DNA accessibility for transcription is regulated by nucleosome positioning. Each nucleosome comprises a histone octamer with two copies each of H4, H3, H2A, and H2B, wrapped by approximately 146 base pairs of DNA. The linker histone H1 connects unpackaged DNA to nucleosomes of varying lengths. Post-transcriptional histone tail modifications, such as methylation, demethylation, acetylation, and deacetylation, alter histone-DNA interactions and control chromatin condensation through the histone code. In plants, transcriptional activation is linked to histone acetylation (e.g., H3K9ac, H3K14ac, H3K36ac), while repression is associated with deacetylation at these sites (Agarwal et al., 2020).

Histone methylation can either activate or suppress genes, depending on the specific modification. For example, methylation of H3K4 and H3K36 is linked to gene activation, while H3K9 and H3K27 methylation are associated with gene repression. In plants, H3K9 monomethylation (H3K9me1) and dimethylation (H3K9me2) mark transposable elements and repetitive sequences in heterochromatic regions, maintaining a repressive transcriptional state. H3K27me1 is found in heterochromatin, while H3K27 trimethylation (H3K27me3) is repressive in euchromatin. H3K27me3 is particularly abundant across the transcribed regions of inactive genes (Liu et al., 2010). Important enzymes including histone methyltransferase (HMT), histone acetyltransferase (HAT), histone demethylase (HDM), and histone de-acetylase (HDAC) are among the many enzymatic tools needed for histone modifications (Grativol et al., 2012). The enzyme histone methyltransferase (HMT) catalyzes the transfer of up to three methyl groups (-CH₃) to the lysine and arginine residues of H3 and H4. A key strategy for plant survival is the expression and silencing of distinct genes in response to a variety of abiotic stimuli (Kumar & Rani, 2023).

13.3.4 DNA methylation

By modifying gene expression in response to climatic stress, DNA methylation plays a critical role in increasing plant tolerance to climate change. The insertion of a methyl group to the cytosine base of DNA is an example of an epigenetic change that

can activate or quiet genes without changing the genetic sequence. Plants may quickly acclimate to climate stressors like drought, heat, or salinity by using DNA methylation to either activate or suppress particular genes involved in stress tolerance. Additionally, DNA methylation can help plants recall previous stressful events, which enables them to respond to future difficulties more effectively. An essential part of plants' resilience to climate change is this adaptation process, which aids in maintaining survival and productivity in the face of shifting climatic conditions (Kumar & Rani, 2023; Penterman et al., 2007).

13.3.5 *Symbiotic relationship*

The role of mycorrhizal symbiosis in climate change Along with these changes, the accompanying microbiome plays an important role. Mycorrhizal fungal species resilience to floods varies depending on the type of tree they are growing on, as well as the intensity and duration of the stress (Johnson, 2018). Several environmental challenges were endured by plants with adaptable, flexible root systems that formed symbiotic associations with mycorrhizal fungi. By spreading their hyphal networks into the soil and gaining access to nutrients and organic molecules that may be beyond the reach of the roots. Mycorrhizal fungi improve nutrient optimization and absorption capabilities, especially phosphorus also encouraging mineralization and availability of nutrients (Lynch, 2013). Several recent investigations have examined mycorrhizal relationships with plant roots and the effects of root symbioses on plants' ability to respond to stresses linked to climate change (Gehring et al., 2017; Lau et al., 2017). High-temperature waves associated with rising solar radiation and CO₂ concentration (Teskey et al., 2015), more severe drought phases (Cook et al., 2018), elevated salinity (Corwin, 2021), and unpredictable flooding events (Alfieri et al., 2017; Tabari, 2020) are scenarios of these abiotic stressors that have a direct connection to poor soils with nutrient deficiencies and affect plants, associated microorganisms and fungal population individually (Treseder et al., 2016). Root-associated beneficial symbionts are expected to improve plant nutrition also the ability of their host trees to adapt to the stress or associated with climate change (Classen et al., 2015; Garcia et al., 2016). Ectomycorrhizal and arbuscular mycorrhizal fungi are associated with 60% of roots of all trees form a fungal sheath around fine roots, thus protecting the plant root and mediating direct interactions with the soil (Steidinger et al., 2019). Arbuscular mycorrhizal fungi are associated with tress in tropical environments such as poplars (Fang et al., 2020), eucalyptus (Adjoud et al., 1996), and olive trees (Calvo-Polanco et al., 2016). Hyphal network structure of mycorrhizal fungi improves soil aggregate stability, soil matrix, and contributes to the formation and maintenance of soil water-macroaggregates (Ji et al., 2019). Also has the ability to modify the root architecture possess greater root hair enhance soil aggregate stability and increase the water and nutrient-absorbing surface area, especially under drought conditions (Liu et al., 2018). Mycorrhizal fungi facilitate several functions such as structural changes in the root system of poplar trees by inducing lateral root formation (Wu et al., 2013), lower the osmotic potential by accumulation of soluble sugars and proline (Wang et al., 2021), improved the water use efficiency in pine (Li et al., 2021a, 2021b), nutrient uptake (Li et al., 2012) and maintain a desirable K⁺/Na⁺ ratio (Frank & Garcia, 2021). There is much proof to support the idea that local beneficial

mycorrhizal fungi are a sustainable tool that can help protect trees from both forest and sustainable agricultural systems from environmental stressors that will only become more frequent and intense as a result of global climate change.

13.4 Conclusion

Climate change presents a significant challenge to ecosystems worldwide, profoundly affecting plant life and their metabolic functions. Secondary metabolism, integral to plant defense, adaptation, and survival, demonstrates both susceptibility and resilience in response to climatic stressors. Plants dynamically adjust their metabolic pathways to cope with rising temperatures, shifting precipitation patterns, and increased CO₂ levels, showcasing exceptional ecological and evolutionary adaptability. Gaining a deeper understanding of the complex interplay between SMs and environmental factors is crucial for recognizing plant resilience and unlocking potential applications in sustainable agriculture, conservation, and biotechnology. Investigating these adaptive mechanisms enhances our ability to comprehend how plants endure and thrive under climate stress, paving the way for innovations that address the adverse effects of climate change on global biodiversity and agriculture.

AI disclosure

During the preparation of this work the author(s) used [NAME TOOL/SERVICE] in order to [REASON]. 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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Impact of xenobiotics under a changing climate scenario: an actualization

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14.1 Introduction

14.1.1 Definition of xenobiotics

Xenobiotics are chemical compounds, which are found in an environment or organism as a “foreign substance.” The definition comes precisely from the Greek terms “xeno” and “biotic,” which refer to “foreign” and “pertaining to life,” respectively (Chen, 2020). Generally, the definition of xenobiotics is associated exclusively with synthetic chemical compounds that are foreign to an organism or environment (Praseetha et al., 2024; Rahman et al., 2024), however, natural compounds (endobiotics) are also considered xenobiotics when they are found in high concentrations (Soucek, 2011). Xenobiotics are developed to be used for agricultural, industrial, domestic, or pharmacological purposes, and cause significant effects on living beings and the environment (Štefanac et al., 2021). These compounds can be found in concentrations ranging from micronutrients to high concentrations, and among their characteristics, which cause their easy bioaccumulation and difficult detection and elimination, stand out their physicochemical structures: small molecular size, polarity, affinity to various solvents, ionizability, and volatility (de Oliveira et al., 2020; Štefanac et al., 2021).

Currently, technological development has brought with it an increase in the use of different chemical substances for different purposes in different ecosystems, in addition to the industrial waste dumped into the environment. All these factors have a considerable impact on biodiversity, both in terrestrial and marine environments, in addition to their documented effects on climate change. It should be noted that their main purpose is not to cause adversities to the ecosystem, but rather the opposite, but on many occasions they end up in environments where their presence is adverse and there is no biotic elimination system, resulting in persistent compounds and, in some cases, increasing their concentration, such as, for example, in food chains (Dubey et al., 2014; Mishra et al., 2019).

14.2 The importance of studying xenobiotics in the context of climate change

There is a great deal of research and theories on how xenobiotics move from their production to their final impact on ecosystems, and on strategies for their elimination (Fewson, 1988; Miglani et al., 2022; Subbulakshmi et al., 2021). However, few studies have documented the relationship between these compounds and climate change, and, in recent years, there has been an increase in the number of studies on the relationship between these compounds and climate change (Barouki, 2024; Mishra et al., 2019; Patel & Kulwant, 2024; Sharma & Kumar, 2024). Environmental conditions are greatly affected by the actions of citizens, causing various factors that have accelerated climate change. Xenobiotics, in particular, play an important role in ecosystems, acting as toxic agents in different species (Barouki, 2024; Ortiz et al., 2022; Sharma & Kumar, 2024). The exponential growth experienced by industries is the main factor that causes xenobiotics to be present in ecosystems in greater quantities every day. Human action has never gone hand in hand with environmental awareness, and it is a hard task to remedy this historical mistake (Fewson, 1988; Miglani et al., 2022).

Weather patterns become more variable as the years go by, being another of the negative results of the manipulation of nature by man. However, in order to eradicate the factors that affect global temperature and climate conditions, it is pertinent to retrace the steps of humanity itself (Andre et al., 2024; Mishra et al., 2019; Ortiz et al., 2022). In an effort to understand the current behavior of the climate, multiple theories emerged, most of which led to pay important attention to xenobiotic compounds. Currently, these are not only theories, but science has demonstrated the negative effect of xenobiotics in all environmental compartments and climatological aspects. Hence, it is of singular importance to study the behavior of different compounds, mainly synthetic compounds, in order to predict their extent and prevent them from being harmful to the environment and ecosystems (Fewson, 1988; Miglani et al., 2022; Mishra et al., 2019; Ortiz et al., 2022).

14.3 Xenobiotics in the environment

14.3.1 *Types of xenobiotics*

The term “xenobiotic” is very broad, with a wide group of substances falling into this category. Qadir et al. (2017) classify them into seven main groups: drugs, environmental contaminants, food additives, hydrocarbons, pesticides, synthetic polymers, and oil mixtures; however, Štefanac et al. (2021) make a more precise classification, derived from the report by Kumar and Chopra (2020), where six main groups of xenobiotics are identified: pesticides, pharmaceutical compounds, personal care products, illicit drugs, industrial products, and nuclear waste. Within these six

groups, subgroups are located in five of them, leaving only nuclear waste without subgroups. The pesticides group includes insecticides, bactericides, fungicides, and herbicides; the pharmaceutical compounds group includes multiple-class pharmaceuticals, endocrine disruptors, essential medicines, antibiotics, psychiatric drugs, and nonsteroidal antiinflammatory drugs and the personal care products group includes fire retardants, fragrances, sunscreen components, antiseptics, and plasticizers. While hallucinogenic compounds, stimulating compounds, and inhibitor compounds are part of illicit drugs, and organic wastes, inorganic wastes, e-waste and heavy metals are subgroups belonging to industrial products.

Piowarska and Kiedrzyńska (2022) divide xenobiotics affecting aquatic ecosystems into petroleum hydrocarbons, polycyclic aromatic hydrocarbons, pharmaceuticals and personal care products, pesticides, dyes, polychlorinated biphenyls and phenolic compounds. Meanwhile, Maqbool et al. (2023), adopt the Water Framework Directive classification, dividing into five groups: pharmaceuticals compounds, pesticides, illicit drugs, personal care products, and other industrial products; a classification very similar to that proposed by Štefanac et al. (2021).

However, industrial development and the production of new compounds cause the scientific community to constantly update the list of xenobiotic compounds. For this reason, it is difficult to define a precise classification of xenobiotic compounds, despite the fact that there is precise knowledge about the large number of these compounds. In addition, another conflicting factor is the factor that is considered to establish the classification, because if we talk about the source of xenobiotics, the particular chemical compound may come from several sources, for example, there are compounds that constitute the active ingredient of several drugs and, at the same time, are found in illicit drugs.

In addition, although the main way of classifying xenobiotics is the one described above, there are other particular ways of differentiating and classifying them. Being differentiated by their physical state, nature, uses, and pathophysiological effects, as shown in Table 14.1.

14.4 Emission sources and dispersion routes

The environment is exposed to xenobiotics from innumerable sources, generally as a result of human action, with no social awareness of the effects of their release. Most of these compounds tend to be persistent in the environment, leading to their accumulation, due to the fact that there are no precise strategies for their elimination, and even when these are available, the volume of production of these compounds exceeds their elimination capacities (Qadir et al., 2017). Štefanac et al. (2021), and Maqbool et al. (2023) identify and differentiate the sources of xenobiotics as direct or indirect, products or processes, deliberate or accidental causes, moving or stationary, and regulated or unregulated (Fig. 14.1). Ben Seghir et al. (2023) classify sources in three ways: natural origin, technological origin, and biotransformation (Figs. 14.1, 14.2, and 14.3).

Table 14.1 Other classifications of xenobiotics (Donner et al., 2010; Gadzała-Kopciuch et al., 2004; Maqbool et al., 2023; Štefanac et al., 2021).

Classification	Types	Characteristics	Environmental distribution	Examples
Physical state	Gaseous	State of aggregation: gas.	They spread easily throughout the ecosystem and can enter individuals through the respiratory tract. They are located in the atmosphere, although they can spread in aerated soils or aquatic systems.	Pesticidas, aerosoles, aromatizantes, drogas ilícitas, hidrocarburos gaseosos, and residuos industriales.
	Powder	Aggregate state: solid. They generally occur as finely divided particles.	Their diffusion capacity is affected; however, climatic factors such as rainfall and windstorms help them to diffuse in soils and disperse in the environment. They can reach groundwater or marine ecosystems, so they are located at the level of the geosphere or hydrosphere.	Pesticides, pharmaceuticals, heavy metals, detergents, and industrial waste.
	Liquid	Aggregate state: liquid.	They diffuse easily through soils and aquatic systems, being mainly influenced by their density and polarity.	Pesticides, pharmaceuticals, dyes and paints, and industrial wastes.

(Continued)

Table 14.1 (Continued)

Classification	Types	Characteristics	Environmental distribution	Examples
Nature	Naturals	Chemical substances naturally occurring in living organisms, mainly molecules synthesized for species defense.	Generally, they are usually found in the individual that produces them naturally. However, the degree of exposure will depend on whether it is secreted or not, in addition to the fact that it may remain in soil or water, or in the specimen that used it as food.	Bacteriotoxins, zootoxins, phytotoxins, serotonin, natural antioxidant compounds, natural gas, and petroleum.
	Synthetics	These are compounds that are generated by human action and that cause damage to ecosystems.	Within this classification there is a great diversity of compounds, produced in different environments, which are distributed in all terrestrial and marine ecosystems.	Food additives, nuclear waste, pharmaceuticals, pesticides, and chemical drugs.
Uses	Actives	Compounds that are developed and used with a defined function or action.	It is difficult to differentiate between active and passive xenobiotics in terms of their distribution, since they are found in the same environments. However, it should be noted that the distribution of active xenobiotics is greater because they are much more frequent; however, when passive xenobiotics are used together with active xenobiotics, they are distributed jointly.	Pesticides, dyes, and paints.
	Passives	Compounds used to enable or facilitate the functioning of active xenobiotics.		Additives and active xenobiotic carrier molecules.

Pathophysiological effects	Organ and tissue damage	Directly affects organs and tissues, commonly bioaccumulates in them.	A large number of xenobiotic compounds, being foreign to organisms, are difficult to eliminate, and instead of being eliminated, they bioaccumulate in tissues and organs, bioaccumulating and biomagnifying. These compounds can be found in all ecosystems.	Renal toxins, microplastics, and heavy metals.
	Affections to biochemical processes	It interrupts or alters biochemical processes, often causing secondary biochemical reactions.	They are generally toxins, hormones or other metabolites produced naturally by one organism that reach another organism where they are not recognized and alter biochemical processes. Therefore, it is common to find them in infected hosts.	Methemoglobin-producing toxins, drugs, hormones.

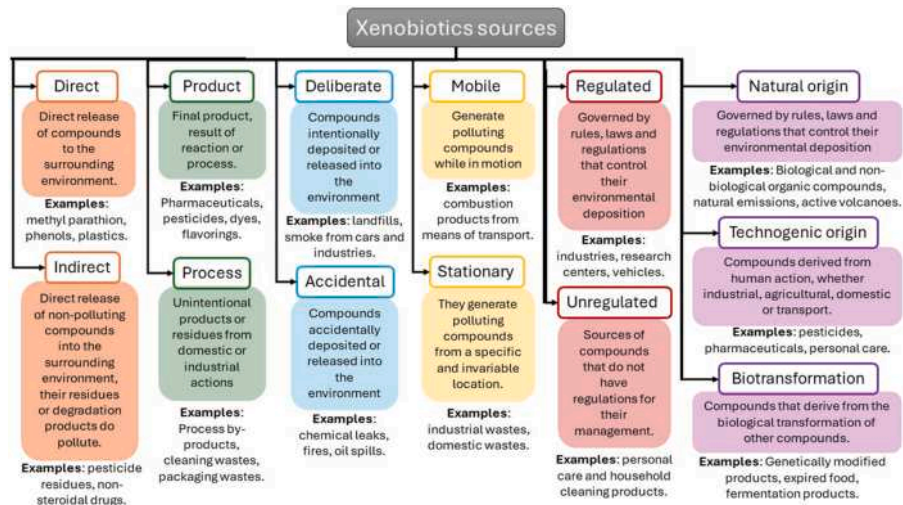


Figure 14.1 Classification of xenobiotic compound sources (Ben Seghir et al., 2023; Maqbool et al., 2023; Štefanac et al., 2021).

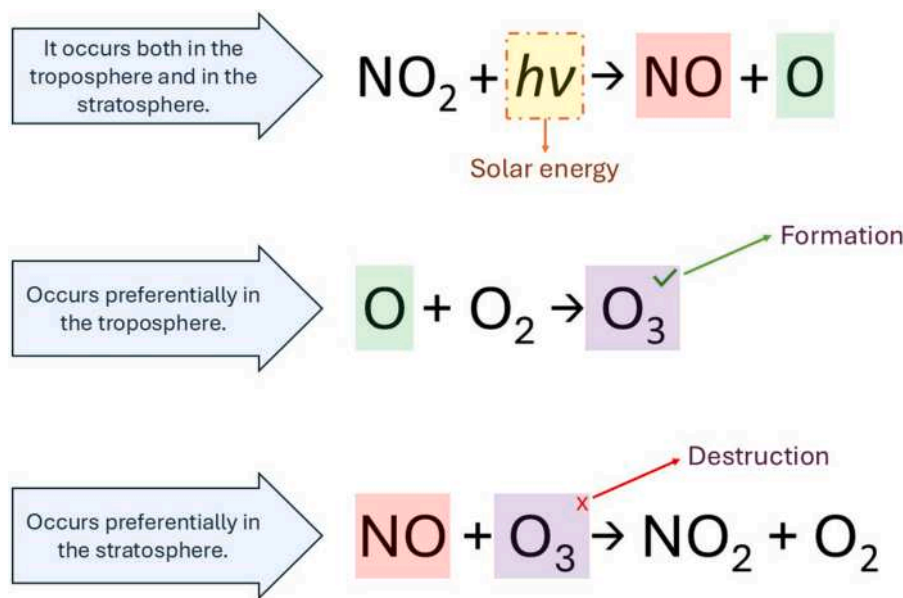


Figure 14.2 Ozone formation and destruction reactions in the atmosphere (Hao et al., 2023; Xie et al., 2023).

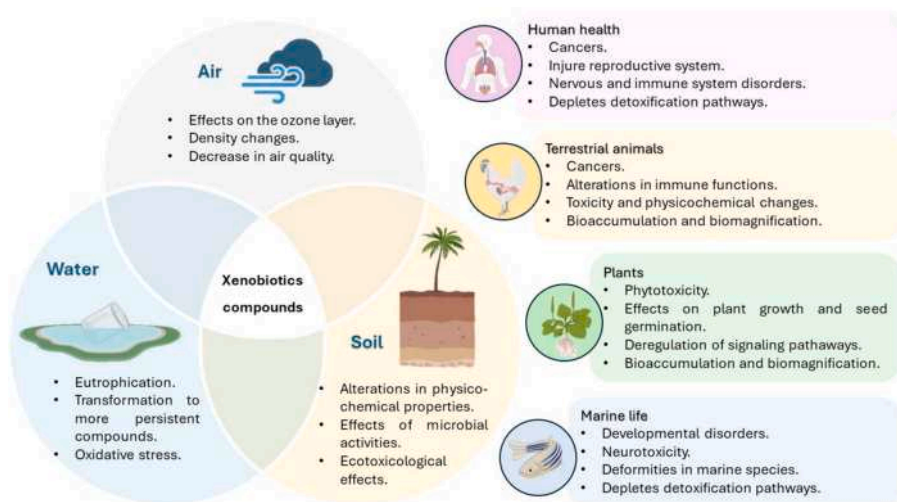


Figure 14.3 Effect of xenobiotics in different environmental compartments and in different organisms.

Source: Modified from Miglani, R., Parveen, N., Kumar, A., Ansari, M.A., Khanna, S., Rawat, G., Panda, A.K., Bisht, S.S., Upadhyay, J., & Ansari, M.N. (2022). Degradation of xenobiotic pollutants: An environmentally sustainable approach. *Metabolites*, 12(9), 818. <https://doi.org/10.3390/metabo12090818>.

For its part, the dispersion of xenobiotics depends considerably on the emission sources and environmental conditions. Dispersion occurs through all environmental compartments: air, water, and soil. In the air, gaseous xenobiotics from various sources, such as industries, vehicles, or volatilization of different chemicals, diffuse easily, dispersing in the atmosphere according to their densities and structures, and can also travel long distances as a result of air currents. In water, distribution occurs due to industrial runoff, wastewater, and agricultural runoff, while ocean currents disperse them throughout the oceans, reaching arctic and subarctic regions. In the case of soils, they can penetrate and adsorb, depending on the physicochemical and biochemical properties of the soil and environmental factors (Bharti, 2024; Hemond & Fechner, 2022; Svavarsson et al., 2021; WingChing-Jones, 2008). These compounds, when harbored in the surrounding environment of living beings, are also capable of penetrating physiological barriers and causing affections in species of all kingdoms. The main routes of entry are oral, for xenobiotics present in food or water, nasal, for gaseous compounds or aerosols, and dermal, the latter being an alternative route for lipophilic products, capable of migrating through the skin. Once inside the organism they are able to cross membranes, either by active or passive transport, and their metabolism involves the detoxification pathways of cytochrome P450, transforming them and aiding their excretion; however, this is not possible in all cases, and compounds even more toxic than the initial compound may be generated (Pant, 2024; Stanley, 2024; Willett & Aluru, 2024).

14.5 Effects on different environmental compartments (air, water, and soil)

The emission and distribution of xenobiotics have consequences in all environmental compartments and for all living beings, as shown in Fig. 14.1. In the atmosphere it causes the gaseous composition of its different layers to be altered, for example, pesticides, volatile organic compounds, chlorofluorocarbons, and polychlorinated biphenyls are harbored in the troposphere, which can also reach the stratosphere, where it is also common to find nitrogen oxides produced by combustion processes (Capella et al., 2023; Shah et al., 2023). Chlorofluorocarbons and nitrogen oxides are of particular relevance to the concentration of atmospheric ozone; however, the current problem is mainly focused on nitrogen oxides, which can act as both precursors and destroyers of ozone (Mirzakhil et al., 2024; Xie et al., 2023). In the troposphere the reaction tends to the formation of ozone from the release of an oxygen atom, which reacts with molecular oxygen and gives rise to ozone, however, in the stratosphere ultraviolet light releases oxygen atoms from nitrogen oxides, resulting in nitrogen monoxide, which destroys ozone by stealing an oxygen atom, reactions shown in Fig. 14.1. In addition, volatile organic compounds that reach the stratosphere can also generate free radicals, contributing to ozone destruction. It should be noted that ozone in the troposphere at high concentrations is a toxic substance for flora and fauna, and its presence in the stratosphere is desirable, but not in the troposphere (Ibrahim et al., 2024; Shah et al., 2023).

Furthermore, xenobiotics in the air can also directly affect living beings, mainly by access through the respiratory tract, lodging in animals in the pulmonary alveoli, or diffusing into the blood, while in plants they enter mainly through the stomata. Among the group of xenobiotic compounds in the air that commonly cause damage to the biosphere are polycyclic aromatic hydrocarbons, heavy metals, pesticides, pharmaceuticals, benzene, sulfur dioxide, nicotine, among others (Mohankumar et al., 2024; Rizikalo et al., 2024; Wei et al., 2023) (Fig. 14.4).

On the other hand, an endless number of xenobiotic compounds are also found in water, which can reach terrestrial organisms through drinking water or through irrigation systems for plants. However, aquatic species are much more affected, and there are multiple reports of bioaccumulation and biomagnification of xenobiotics, their magnification being favored by trophic chains (Bhatt & Chauhan, 2023; Liang et al., 2023; Saidon et al., 2024). The main sources of these compounds in the hydrosphere are sewage, displacement of surface compounds by rainfall and irrigation systems, industrial effluents, fossil fuel leaks, underwater volcanoes, and deposition of airborne particles (Rahman et al., 2024). As they diffuse easily in the aqueous medium they alter the composition and oxygenation of the water with ease. Remembering that chemistry and biochemistry state that water is the main medium for chemical reactions to occur, it is easy to conclude that these new compounds entering the hydrosphere can react with aquatic components and may affect the bioavailability of aquatic nutrients (Akiya & Savage, 2002; Nelson et al., 2008).

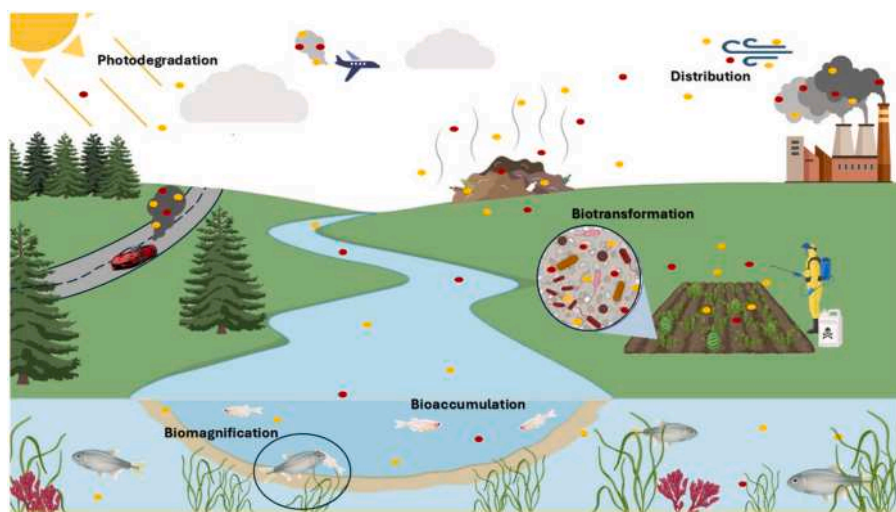


Figure 14.4 Environmental distribution of xenobiotic compounds.

Eutrophication (excessive nutrient enrichment) can be caused by the entry of xenobiotics containing nutrients such as nitrogen and phosphorus into water bodies, causing excessive algae development, which blocks light and affects the photosynthesis of other aquatic plants, in addition to the fact that several algae produce toxins which, upon decomposition, consume oxygen and cause areas of hypoxia or anoxia, making it impossible for life to develop (Kornijów, 2024; Lukhele & Msagati, 2024). Furthermore, pollution by paints and dyes affects the systems causing a similar effect to excessive algae development, blocking light and preventing gas exchange (Abdelkader et al., 2011). While, when passing into the interior of marine organisms these compounds affect homeostasis, causing an overproduction of reactive oxygen species and causing oxidative stress. In addition, fish embryos are highly sensitive, being able to retard growth, mutagenicity, or even death (Arya & Haq, 2019; Ibor et al., 2019; Rahman et al., 2024). The lack of effective biological mechanisms for the elimination of these compounds causes them to lodge in different organs and tissues, such as the liver, kidneys and gills, which can cause cell damage and negatively interfere in the development of vital functions, for example, microplastics have been documented in food webs in coral reefs (Miller et al., 2023), heavy metals in tuna (Aziz et al., 2024) and other fish and crustaceans (Bobrowska-Korczak et al., 2021; Younis et al., 2024), pesticide residues in fish (Abbassy et al., 2021; Slaby et al., 2022), pharmaceutical products in shellfish (Mello et al., 2022) and fish (Bobrowska-Korczak et al., 2021), among others.

For the Earth's land surface, the geosphere, xenobiotics also constitute a notable problem, with soils being highly contaminated as a result of agricultural activity and industrialization (Iqbal et al., 2020; Kirici & Sökmen, 2024). The physical state of the soil allows many of the xenobiotic compounds to present a particularly harmful

property for the environment, their moderate to long-lasting stability, which confers them a great persistence (Liu et al., 2020; Rahman et al., 2024). Their dispersal is greatly influenced by soil properties, climatic factors, and microorganisms. In addition, in soil, xenobiotics are generally adsorbed to components or are naturally processed by soil microorganisms. Adsorption naturally, without biotic factors, is mediated primarily by soil composition and its pH and redox potential (He et al., 2024; Kapoor & Zdarta, 2024; Madawala, 2023). Microorganisms also play a key role in the mobility of xenobiotics, especially in bioavailability and toxicity. Xenobiotics are employed by them as a source of carbon or other substrates, degrading them and, in most cases, decreasing their toxicity, however, generating compounds more akin to biological systems, increasing their bioavailability. In addition, many microorganisms also secrete extracellular enzymes, which can affect the structure of xenobiotics even outside the cell, for example, increasing the bioavailability of heavy metals (Madawala, 2023; Urana et al., 2023).

14.6 Climate change and its impacts on environmental processes

14.6.1 *Changes in global temperature and weather patterns*

The global temperature has experienced a marked upward trend in recent decades, increasing by 0.2°C per decade. The increase in greenhouse gases has caused a greater absorption and emission of energy in the form of heat in the atmosphere, being the production of these gases the main factor that has led to the increase in global temperature, and multiple greenhouse gases are xenobiotic compounds, or endobiotics at high concentrations, also acting as xenobiotics. Meanwhile, the abnormal increase in the surface temperature of the central and eastern Pacific Ocean (El Niño phenomenon) also has a marked influence on global temperature, increasing it as a result of changes in oceanic and climatic patterns (Arnell et al., 2019; Hansen et al., 2006; Mikhaylov et al., 2020; Mokhov, 2022). In addition, the El Niño phenomenon causes more extreme weather conditions, altering climate patterns, exacerbating periods of drought or rainfall in different regions, and increasing the climatological differences between different regions (Mokhov, 2022; Pécastaing & Chávez, 2020). Furthermore, to the El Niño phenomenon, alterations in weather patterns are highly influenced by the increase in global temperature and the increase in human activity, with greenhouse gases, deforestation, land use change being triggering factors. The main meteorological effects that are currently having the greatest impact are hurricanes, heat waves, extreme droughts, and torrential rains (Akhtar, 2020; Majedul Islam, 2022; Trenberth, 2018).

14.7 Alterations in biogeochemical cycles

The processes of movement and transformation of chemical elements between biotic and abiotic factors are managed through different cycles, which constitute the

biogeochemical cycles. These cycles include sedimentary, water, carbon, nitrogen, and oxygen, among others (Bertrand et al., 2015; Singh, 2024). Phenomena such as soil erosion and sedimentation in watersheds are phenomena that have increased as a result of climatic factors such as precipitation, windstorms, and snowmelt. The water cycle has also been altered; global temperature and changes in weather patterns, together with the presence of xenobiotics in water and air, have affected evaporation, condensation, and precipitation processes, affecting their infiltration into soils and runoff, influencing their biological disposition (Raimi et al., 2021; Singh, 2024). Chemical element cycles are no exception, soil minerals have been greatly affected by various human activities, primarily agricultural systems and mining, while carbon, nitrogen, and oxygen cycles are also influenced by greenhouse gas emissions and changes in air composition (Burgin et al., 2011; Raimi et al., 2021).

14.8 Interactions between xenobiotics and climate change

14.8.1 *Modification in the degradation, transport, and distribution of xenobiotics due to climate change*

The scope of climate change in the different phenomena and processes experienced by xenobiotics is a phenomenon whose true magnitude is not yet known with certainty; however, it is a problem that is in the sights of many researchers. Climatic variations alter the life cycles and migratory phenomena of multiple species, causing an increase in the distribution of diseases, vectors, and pests. This causes them to adapt to new conditions, which may increase their reproduction for animals, sporulation for fungi, or proliferation for microorganisms and diseases, in addition to generating new resistance and virulence factors. As these species increase, more drugs, pesticides, and cleaning products, among other products, are needed to combat them and mitigate economic or human losses. Therefore, there is a need to apply more xenobiotic products (Johnson & Jones, 2017; Ma et al., 2021; Tudi et al., 2023). In addition, as the migration of species increases, the need arises to incorporate new foods into their diet, influencing the bioaccumulation and biomagnification of xenobiotics, mainly in marine species. Bioaccumulation in different predator–prey is involved not only in the transport and distribution of xenobiotics but also influences their toxicity and bioavailability (Córdoba-Tovar et al., 2022; Zenker et al., 2014). In turn, the alteration of biogeochemical cycles also causes the use of more xenobiotic compounds, for example, soil erosion and nutrient runoff imply a greater need for agrochemicals (Singh, 2024; Tudi et al., 2023).

However, climate change not only affects living organisms but also has a direct influence on xenobiotic compounds. The increase in global temperature has caused compounds to become more volatile, lasting longer in the atmosphere and being able to travel greater distances, with changes in air current patterns also having a considerable influence (Barouki, 2024). In addition, heavy rainfall, rising sea levels,

and marine currents have favored the transport of xenobiotics in the hydrosphere and, therefore, a greater distribution of these compounds (Raimi et al., 2021; Singh, 2024).

The degradation of xenobiotics is also largely mediated by environmental and climatic parameters. However, it should be noted that it is precisely xenobiotics are so dangerous because of their complex structure, which makes them difficult to degrade. Despite this, three fundamental mechanisms of xenobiotic degradation occur in nature: biodegradation, photodegradation, and oxidation–reduction reactions (Štefanac et al., 2021; Wang et al., 2022).

Biodegradation consists of a living organism (mainly microorganisms) degrading the xenobiotic compound, transforming it into a nontoxic substance. There are about 50 documented microbial strains that have been demonstrated to degrade xenobiotics (Gadzała-Kopciuch et al., 2004; Štefanac et al., 2021). Microbial degradation occurs by mineralization or cometabolism processes. In cometabolism xenobiotic substances are partially degraded, giving rise to less toxic compounds, while in mineralization microorganisms use xenobiotics as substrates, serving them as carbon and energy sources, employing complex enzymatic pathways that degrade the compounds completely, down to inorganic matter (Arora et al., 2022). Biodegradation consists of three steps: adsorption of the xenobiotic on the cell surface, penetration into the cell depending on the chemical structure of the xenobiotic, and, finally, enzymatic degradation to simpler compounds. The mechanisms involved in the degradation of xenobiotic compounds involve processes of oxidation, reduction, hydrolysis, dehydrogenation, dehalogenation, decarboxylation, rearrangements, conjugations, isomerization, among others (Bose et al., 2021; Hugo et al., 2016). An example of biodegradation by cometabolism is the passage of endosulfan (toxic organochlorine pesticide) to endosulfan ether, endosulfan diol, and endosulfan lactone, metabolites with considerably lower toxicity than the original precursor (Bose et al., 2021; Kamei et al., 2011). Whereas, an example of mineralization is the microbial degradation of 4-nitrophenol (xenobiotic used in the production of drugs, fungicides, and dyes) to carbon dioxide and water (Arora et al., 2022). It should be noted that partial degradation of xenobiotics by cometabolism or other abiotic mechanisms can result in compounds with even greater toxicity, triggering a more severe problem, so it is crucial to know the transformation pathways of these compounds in order not to cause more environmental problems (Štefanac et al., 2021).

Photodegradation consists of the absorption of photons from infrared, ultraviolet, and visible solar radiation, with this absorbed energy causing the breaking of bonds and the consequent degradation of xenobiotic compounds. Among the xenobiotics capable of undergoing this degradation phenomenon are pesticides, heavy metals, and dyes, as well as some photodegradable drugs or polymers. Sertraline is a drug that can be found in surface waters and is susceptible to direct photolysis, constituting its main transformation pathway, in addition, reactive species catalyze the degradation process of the compound (Gornik et al., 2020; Štefanac et al., 2021). Oxidation–reduction reactions are the least common mechanism of degradation of xenobiotics; however, in spite of this, several xenobiotic compounds are capable of undergoing electron transfer transformations, reducing their toxicity, as is the case of some pesticides (Wang et al., 2022).

14.9 Impact of climate change on the toxicity and bioavailability of xenobiotics

The toxicity and bioavailability of xenobiotic compounds are largely determined by their chemical structure and molecular size, influencing their affinity to biological systems and their ability to migrate across different membranes and physiological barriers (Gupta et al., 2022; Smułek & Kaczorek, 2022). For example, xenobiotics with lipophilic chemical structures are generally more persistent in the environment, in addition, they are affinity with cell membranes, making possible their accumulation in lipid tissues, and at the same time, their low affinity with water makes their excretion through urine or feces difficult. These factors cause it to have greater potential toxicity, being able to alter homeostasis through antioxidant imbalance due to the production of reactive oxygen species (Kish et al., 2023).

Climate change also influences bioavailability and toxicity. The increase in global temperature and the incidence of solar radiation causes organisms to suffer an increase in oxidative stress, leading to greater sensitivity to the toxicity of xenobiotic compounds, such toxicity being the product of synergism between environmental conditions and xenobiotics (Grenier et al., 2023; Zeliger, 2022). An example of this is the increase in the appearance of skin cancer as a result of the combined effect of ultraviolet rays and xenobiotics in the air (ozone, polycyclic aromatic hydrocarbons, nitrogen oxides, and volatile organic compounds), increasing the production of free radicals and the prevalence of skin cancer (Burke, 2021). In addition, meteorological phenomena increase bioavailability and toxicity due to increased concentration (Piwowarska & Kiedrzyńska, 2022). For example, drought causes the concentration of xenobiotics in water to be higher (Noyes et al., 2009), and the increased production of tropospheric ozone and other pollutants aggravate the respiratory inhalation of these compounds, in addition to enabling complex interactions that can lead to compounds of greater toxicity as a synergistic effect, but in this case, among several xenobiotics (Barouki, 2024).

On the other hand, the biological processes of transformation of these compounds, as mentioned above, can result in products with a higher level of toxicity than the initial compound. This is because the fundamental objective of their metabolism is to transform them into compounds with a greater affinity with the biological system, in order to facilitate their mobilization and excretion. However, not in all cases the result is a less toxic compound and, as they are metabolites that are more affine to the organism, they can cause greater damage, as their bioavailability increases. If this situation is added that the metabolites turn out to be more toxic than their xenobiotic precursor, then the toxicological effects will be considerably aggravated (Filimonov et al., 2023; Orhan, 2021; Štefanac et al., 2021). An example of a xenobiotic compound whose transformation results in a more toxic and stable compound is parathion (an organophosphate insecticide), which is transformed into paraoxon, this metabolite exerts a significantly higher acetylcholinesterase inhibitory capacity than its precursor, causing more severe neurotoxicity (Militani et al., 2024).

14.10 Impact of xenobiotics on climate change and biogeochemical cycles

Xenobiotics can have both direct and secondary effects on global temperature and climatic conditions, just as climate change also affects these compounds (Sharma & Kumar, 2024). Xenobiotics that affect the ozone layer have a considerable impact on global temperature because, by destroying ozone, the main molecule responsible for protecting the planet from solar radiation, they weaken the protective barrier and increase the incidence of the sun's rays, increasing the absorption of infrared radiation by carbon dioxide, leading to a consequent increase in global temperature (Ibrahim et al., 2024; Roy, 2020; Shah et al., 2023). Xie et al. (2023) show that, despite the awareness of the population regarding the care and protection of the ozone layer, surface ultraviolet radiation in the tropics and northern mid-latitudes increased by approximately 60.0 Jm^{-2} , in the period from 2010 to 2020, evaluating the periods from May to September. In addition, air currents containing large amounts of xenobiotics are usually denser, affecting their velocity and displacement (Bulucea et al., 2015).

In addition, biogeochemical cycles are also affected, for example, the carbon and nitrogen cycles are mediated by microorganisms, which can be affected by various xenobiotics and interfere with their function. Soil fertility is related to nitrogen fixation by microorganisms, while carbon stored in aquatic ecosystems is due to aquatic microorganisms. If xenobiotics inhibit the development of such microorganisms, not only are the nitrogen and carbon cycles affected, but also the living conditions necessary for the development of the life of multiple terrestrial plants or aquatic organisms, respectively, are altered (López, 2002; WingChing-Jones, 2008; Zhou et al., 2021). As mentioned above, xenobiotics containing minerals can cause eutrophication in aquatic ecosystems, interfering not only in the cycles of these nutrients but also in the oxygen cycle, because when they decompose they consume the oxygen present. Furthermore, just as there are xenobiotics that favor the development of algae and other aquatic plants, there are xenobiotics that inhibit them, decreasing photosynthesis and, therefore, oxygen production in marine environments (Kornijów, 2024; Lukhele & Msagati, 2024; Pawłowska & Biczak, 2024). An example of the inhibition of photosynthetic oxygen production is the research conducted by Menone and Pflugmacher (2005), where they identified that the higher the concentration of 3-chlorobiphenyl, the lower the oxygen production by *Ceratophyllum demersum*.

14.11 Effects on human health and ecosystems

14.11.1 Human health risk assessment due to xenobiotic exposure under climate change conditions

Humans, being the main producers of xenobiotic compounds, are exposed to them from a very early age. These compounds have different adverse effects, such as cancer, accelerated aging, atherosclerosis, cardiovascular diseases,

neurodegenerative, endocrine, and reproductive disorders, ischemia-reperfusion injury, insulin resistance, diabetes mellitus, microbiological alterations in the gastrointestinal tract, among others (Madhu et al., 2022). Compounds such as bisphenol A, benzo- α -pyrene, and phthalates act as endocrine disruptors, altering the hormonal complex and, therefore, homeostasis (Goralczyk, 2021). In the nervous system, organophosphorus pesticides induce neuropathy due to the phosphorylation of acetylcholinesterase or the target esterase of neuropathy, in addition to causing cholinergic crises, intermediate syndrome, and chronic neuropsychiatric disorders (Ganie et al., 2022). On the other hand, heavy metals also have effects on the nervous system, for example, arsenic (inorganic is more toxic than organic) affects the transmission of signal transduction from the peripheral nervous system to the central nervous system, acts synergistically with dopamine causing neurotoxicity, in the brain it causes inflammation and oxidative damage, it disrupts the regulatory connections between the hypothalamic–pituitary–adrenal axis and the serotonergic system in the dorsal hippocampus, it has neurotoxicity on the neurotransmitters responsible for communication between brain cells. In addition, heavy metals not only damage the nervous system but also increase the production of reactive oxygen species, cause mitochondrial dysfunction and chromosomal aberrations, and damage cellular DNA (Thakur et al., 2021).

As discussed above, climate change influences the distribution, bioavailability, and toxicity of xenobiotics, increasing the risk posed by these compounds to human health and all species in general. A clear example is the concentration of heavy metals, pharmaceuticals, and pesticides in waters for human consumption (Barouki, 2024; Mishra et al., 2019). While a more illustrative example of a particular group of xenobiotics could be the case of polychlorinated biphenyls. These substances are persistent organic pollutants, whose degradation rate depends considerably on climatic factors, in addition, the rise in global temperature causes a greater volatilization of these compounds, while rainfall brings with it their concentration in aquatic bodies, both factors causing an increase in their distribution and toxicity. Furthermore, polychlorinated biphenyls can be transformed into more toxic compounds, such as dioxins and furans, by the action of microorganisms or by the presence of other chemical compounds, this transformation being catalyzed by sunlight. In human health, polychlorinated biphenyls can induce immune disorders, neurodegenerative disorders, and an increased risk of cancer, while dioxins and furans present more acute effects than their precursors, presenting more aggressive mechanisms of action, being potentially carcinogenic, greater impact as endocrine disruptors and greater capacity for bioaccumulation due to their higher lipophilicity (Bursian et al., 2011; Fernández-González et al., 2015; Lamon et al., 2009).

14.12 Impacts on biodiversity and ecosystem functioning

Throughout this chapter, important guidelines have already been established on the effects of xenobiotics on ecosystems, such as alterations in microbial communities

and aquatic habitats (Arora et al., 2022; Kornijów, 2024; Lukhele & Msagati, 2024), as well as influencing the migratory routes of multiple species (Punia et al., 2023); however, there are many more examples of their impact. In particular, xenobiotic compounds can be taken up by multiple species, not only animals but also plants, and alter food chains. For species with a long-lifecycle, bioaccumulation is more significant, and if we add to this the fact that many of the species, when they reach an advanced age, are the target prey of multiple predators or even scavenger species, the biomagnification factor is increased (Wu et al., 2024).

In order to understand the magnitude of xenobiotics on biodiversity and ecosystem functioning, it is easiest to select a particular ecosystem to identify all the factors (Fig. 14.5). Wetlands and estuaries are very susceptible ecosystems to both climate change and xenobiotic compounds, multiple wetlands disappear at periods of the year, depending on climatic conditions, with a key factor for these ecosystems being the frequency and intensity of rainfall (Majumdar et al., 2020; Mohapatra et al., 2021). In these shallow water bodies, xenobiotic compounds tend to accumulate, which can reach them through runoff or environmental waste, and when the water evaporates at one time of the year, they are more easily fixed to the soil and persist, resulting in an increase in their concentration (Nottingham & Messer, 2021; Noyes et al., 2009). The humidity and concentration not only of xenobiotics, but also of diverse nutrients, make them rich environments for microbiota and aquatic animals. In wetlands and estuaries, bioremediation occurs naturally, because many microorganisms are able to degrade xenobiotic compounds, for example, several strains of freshwater proteobacteria are able to transform up to 81% of sulfamethoxazole by cometabolism (Reis et al., 2018). However, these organisms are not immune to all xenobiotic compounds, and being of small sizes, they are very susceptible to low concentrations of xenobiotics, influencing their biodiversity, as is the case of glyphosate, which is toxic to phytoplankton and other plant species (y García et al., 2022).

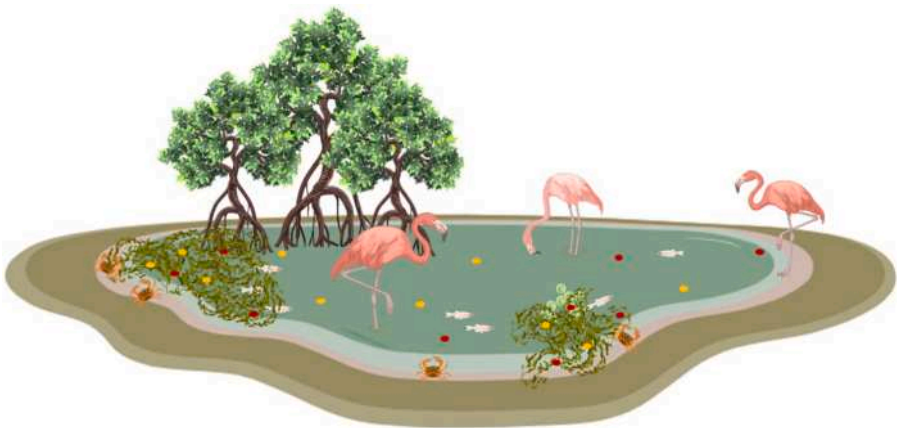


Figure 14.5 Wetland as a model ecosystem for bioaccumulation and natural bioremediation of xenobiotics.

On the other hand, if phytoplankton blooms are favored, their volume on the surface will increase, restricting light penetration and affecting underwater species, in addition to decreasing the ability of predators to pursue and trap their underwater prey (Aranguren Díaz et al., 2022). Moving on to trophic chains, for example, crustaceans and fish that live exposed to high concentrations of xenobiotics, bioaccumulate large amounts of xenobiotics, and when predators feed on them, the presence of these compounds is biomagnified, having adverse effects on their natural predators. For example, flamingos commonly feed on these species, and even raise their offspring in these ecosystems, being exposed to multiple xenobiotics throughout their lives, suffering endocrine disorders that affect their reproduction and being more susceptible to oxidative stress, as well as influencing their migratory patterns. An example of a xenobiotic identified in flamingos is heavy metals (Bodziach et al., 2021; Gillingham et al., 2021). In addition, fry of many species lives in shallow water (wetlands and estuaries), avoiding being eaten by larger fish, bioaccumulating multiple xenobiotics before moving out to deeper water, influencing the distribution of these compounds (Wainwright et al., 2001; Wang et al., 2019).

14.13 Mitigation and adaptation strategies

14.13.1 *Emerging technologies for xenobiotic remediation*

The growing awareness of mankind of the impact of xenobiotics on the environment has brought about the incursion into the area of remediation. The remediation of these compounds can be carried out by different methods: physical, chemical, biological, or even hybrid (Priya et al., 2024). Physical remediation consists of using a physical method for the elimination, containment, or immobilization of the compounds, such as adsorption processes, vapor extraction, or soil washing (Aparicio et al., 2022). Chemical remediation involves reactions of decomposition or inactivation of xenobiotics, mainly by oxidation or reduction (Karthigadevi et al., 2021). Biological remediation or bioremediation involves living organisms, which have enzymatic machinery capable of degrading these compounds, mainly using plants, fungi, or microorganisms. However, there are remediation processes that involve more than one of these methods, hence it is called hybrid remediation, such as electrochemical treatments, adsorption combined with a chemical immobilization reaction, membrane bioreactors, or microbial biodegradation coupled with phytoremediation for accumulation in plant tissues (Priya et al., 2024).

Currently, bioremediation stands out among emerging technologies because it is a versatile technology that, in addition to eliminating pollutants, also promotes the development of ecosystems, being a sustainable, efficient, cost-effective and noninvasive technology (Joshi et al., 2024; Ossai et al., 2022). However, it is a more delicate process, due to the fact that it is developed with living organisms, in addition, it is greatly influenced by climatic factors and by the native species of the ecosystems, being influenced by the characteristics of each bioremediation organism and by the structures of the xenobiotic compounds (Joshi et al., 2024; Sharma, 2021). In addition, there are also novel studies where nanotechnology has been used for

remediation purposes, developing nanoadsorbents, nanofilters, nanoporous membranes from nanofibers, nanocomposites, nanosponges, nanosensors, and metal nanoparticles because of their large number of reaction sites on the surface and because they can absorb contaminants and give less hazardous products (Karthigadevi et al., 2021).

14.14 Policies and regulations for the management of xenobiotics under climate change scenarios

Currently, effective policies and regulations are essential to mitigate the risks associated with these persistent pollutants, which can have detrimental effects on ecosystems, human health, and biodiversity. This topic explores the current landscape of policies and regulations for xenobiotic management, identifies gaps and challenges, and proposes recommendations for improving governance in the context of climate change.

Many countries have established regulatory frameworks to manage the risks posed by xenobiotics, particularly in sectors like agriculture, industry, and waste management. For example, the Toxic Substances Control Act (TSCA) in the United States regulates the manufacture, import, and use of chemical substances, including xenobiotics (Gupta, 2020). Similarly, the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation in the European Union mandates the assessment of the risks associated with chemical substances before they can be marketed (Pistollato et al., 2021).

However, while these regulations provide a foundation for managing xenobiotics, they often fail to adequately account for the dynamic nature of climate change. Many existing frameworks are reactive rather than proactive, focusing primarily on assessing and regulating known risks without considering the evolving environmental conditions that can alter the behavior and toxicity of these substances.

Challenges in current frameworks

1. **Dynamic environmental changes:** Climate change alters temperature, precipitation, and soil conditions, affecting the behavior and degradation of xenobiotics. Current regulations may not be flexible enough to adapt to these changes, leaving gaps in risk assessment and management.
2. **Data gaps:** There is often a lack of comprehensive data on the long-term impacts of xenobiotics, particularly under varying climate conditions. Insufficient research hampers policymakers' ability to create informed regulations.
3. **Interconnected risks:** The impacts of xenobiotics do not exist in isolation; they often interact with other environmental stressors exacerbated by climate change, such as air pollution or habitat loss. Current policies may not adequately address these interconnected risks.

Recommendations for improved governance

1. **Adaptive regulatory frameworks:** Policymakers should develop adaptive management strategies that can evolve alongside changing climate conditions. This includes incorporating regular reviews and updates to existing regulations based on the latest scientific data and environmental monitoring.

2. Integrative risk assessment: Regulatory frameworks should emphasize a more holistic approach to risk assessment that considers the combined effects of xenobiotics and climate change. This approach could involve integrating assessments across multiple sectors (agriculture, industrial, and environmental) to identify synergistic risks.
3. Strengthening research and monitoring: Increased funding for research into the effects of xenobiotics under climate change scenarios is crucial. Long-term environmental monitoring programs should be established to gather data on the persistence and toxicity of xenobiotics, enabling policymakers to make informed decisions.
4. Stakeholder engagement: Involving a broader range of stakeholders—such as local communities, environmental organizations, and industry representatives—in the policy-making process can help identify practical solutions and ensure that regulations are effective and equitable.
5. International collaboration: Given the transboundary nature of many xenobiotic pollutants, international cooperation is essential for effective management. Collaborative efforts can include shared research initiatives, harmonization of regulatory standards, and collective action to address the global dimensions of xenobiotic pollution.

14.15 Future research and challenges

14.15.1 *Research needs in the area of xenobiotics and climate change*

The impact of xenobiotic compounds coupled with climate change still presents areas of interest that have not been covered by current research. It is necessary to continue defining guidelines that help to understand the synergistic and antagonistic processes between these factors. A current problem is the resistance that pests have developed to xenobiotic compounds designed to combat them, and climate change may be a determining factor in the perception of this phenomenon. This same problem means that higher and higher concentrations of these compounds are required to eliminate them, causing greater contamination. Another window of opportunity is the understanding of the specific mechanisms of action developed by pests, in order to predict their response and develop compounds that are more effective at lower concentrations (IPPC Secretariat, 2021).

For its part, remediation is a widely researched science, but more tools are needed than those currently available because, for example, a plant used in Brazil for phytoremediation of xenobiotics cannot be used in the climatic conditions of Canada, because it would not develop, and remediation species can be used for specific geographic regions, but not globally in the same strategy, and the chemical nature of the xenobiotics in question also depends (Joshi et al., 2024; Yap et al., 2021). Climate change also alters habitats, causing the displacement of natural enemies of pests or the proliferation of more resistant diseases, thus creating the need to resort to new management and sanitation alternatives that, if applied without first studying their possible environmental repercussions, would cause greater problems than those they were originally intended to combat. In addition, a factor that cannot be left unmentioned is multidisciplinary research, where the sources of knowledge are both experts in the area and people who work close to the problem in question and are

probably the first to identify or suffer the adverse effects of climate change and xenobiotics in the different ecosystems ([IPPC Secretariat, 2021](#)).

14.16 Databases and the development of predictive models for xenobiotic behavior

The accelerated development of bioinformatics has generated a considerable link between computer science and biological models. Computer science helps to estimate the behavior of different biological factors when subjected to adverse factors, such as xenobiotics or climatic changes, through predictive models, employing probabilistic models and shortening response times ([Kumari & Kumar, 2021](#)). [Arora et al. \(2022\)](#) mention in their study the most relevant bibliographic, chemical, and biodegradation databases related to xenobiotic compounds. The most relevant bibliographic databases are SCOPUS and PubMed, while the most complete and freely accessible database related to chemical structures and properties is PubChem, which also offers data on biological activities, toxicity, and safety. However, there are others such as the EU Pesticide database, Chemical and Products Database (CPDat), CompTox Chemistry Dashboard, Aggregated Computational Toxicology Online Resource (ACToR), ContaminantDB, and Distributed Structure-Searchable Toxicity (DSSTox) ([Arora et al., 2022](#); [Judson et al., 2008](#); [Richard & Williams, 2002](#); [Williams et al., 2017](#); [Wishart, 2017](#)). While, in the area of biodegradation are EAWAG-Biocatalysis/Biodegradation Database (BBD), Plastics Microbial Biodegradation Database, Organonitrogen Degradation Database, Food Risk Component Database, and Aromatic hydrocarbon Degrading Database ([Arora et al., 2022](#); [Duarte et al., 2014](#); [Ellis et al., 2006](#); [Gan & Zhang, 2019](#); [Robinson et al., 2021](#); [Williams et al., 2017](#); [Zhang et al., 2020](#)). However, the previously stated databases collect information, but do not develop predictive models. Although there are multiple researches that define the various pathways of xenobiotics in nature and living organisms, there is a need to investigate this behavior in a changing climate scenario, the best alternative being predictive models, based on pre-existing research, but adding current factors of relevant impact.

14.17 Challenges in the implementation of management strategies

Although multiple researches are developed to combat xenobiotics in a changing climate scenario, the scope of these is not enough. Human needs, disease prevalence, agricultural territories, and industrial development are increasing, bringing with them an increase in the production and use of xenobiotic compounds, making it a major challenge for science to keep pace with this increase. In addition, economic and production issues slow down business change and the development of policies that cause society to become more environmentally responsible ([Zhang et al., 2022](#)). For example, many producers have implemented organic agriculture practices, where the

use of agrochemicals and other xenobiotic compounds is avoided for the production of higher quality food, however, the price of these products is higher, due to the cultivation practices themselves and the lower volume of production, being less accessible productions for a large part of society (Gamage et al., 2023). In addition, another problem is the implementation of documented environmental remediation processes, because many of these studies have not been developed in the environment, but have been developed on a laboratory scale, and it is necessary to evaluate all the influential variables in their environmental application (Aparicio et al., 2022). Meanwhile, the efficiency of the implemented methods and of the most novel ones, studied in the environment, needs to be increased in order to achieve an elimination capacity equal to or higher than that of the production of these compounds (Saravanan et al., 2022). On the other hand, another challenge is the need for a global consensus for the management of this problem, where there is an environmental commitment above the current global conflicts (Newig et al., 2020). There are many challenges facing humanity to achieve a balance between production and the environment, however, as a positive factor, it should be noted that awareness has increased and current research has yielded promising results in this area, being a matter of time and willpower to detoxify the planet, and the development of human life does not overlap with the development of the rest of the species.

14.18 Conclusions

In conclusion, the impacts of xenobiotics on the environment and human health are significantly exacerbated by climate change, which increases their toxicity, bioaccumulation, and persistence in environmental compartments such as air, water, and soil. These pollutants, resistant to natural degradation processes, pose growing risks to ecosystems and public health, especially in a warming climate that amplifies their absorption and harmful effects. Emerging remediation technologies, including advanced bioremediation with genetically engineered microorganisms, phytoremediation using pollutant-absorbing plants, and nanotechnology-based filtration systems, offer promising solutions to mitigate these negative impacts. Looking forward, the continuous development and refinement of these remediation technologies will be essential, as well as their integration into sustainable, climate-adaptive strategies. Future perspectives should also include fostering interdisciplinary collaboration among researchers, regulators, and industry to advance real-time detection, removal, and control of xenobiotics, enabling more immediate responses to their effects. Additionally, regulatory policies must evolve to address the compounded impacts of xenobiotics and climate change, promoting research into less persistent and safer compounds. Enhanced public awareness and education about the risks associated with xenobiotics and climate change are vital to support these efforts. Implementing these innovative approaches and proactive regulations will significantly reduce the risks associated with xenobiotics, protecting both human health and ecosystem stability in an increasingly climate-challenged world.

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Impact of climate change on food security and plant disease management

15

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15.1 Introduction

The food security concept has evolved through the years to include essential aspects for a functional alimentary system. One of the first definitions was mentioned at the 1974 World Food Conference: “the availability at all times of adequate world food supplies of basic foodstuffs, particularly to avoid acute food shortages in the event of widespread crop failure, natural or other disasters, to sustain a steady expansion of food consumption in countries with low levels of per capita intake and to offset

fluctuations in production and prices” (United Nations Report of the World Food Conference Rome, 1974). The concept was established on four important pillars: availability, access, utilization, and stability. A more recent and refined definition of food safety was presented in the 2001 Food and Agriculture Organization (FAO) report on *The State of Food Insecurity in the World*, which states: “Food security exists when all people at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life” (FAO, *The State of Food Insecurity in the World*, 2001). Thus, for food to be adequate and available, it is essential not only to ensure enough supplies by maintaining high production yields but also to increase the nutritional value and safety of the produced aliments. Furthermore, two more pillars were recently emphasized by Clapp and collaborators: agency and sustainability (Clapp et al., 2022). Agency refers to the individual's capacity to determine their own and their community's well-being, while sustainability involves the “ability of food systems to provide food security and nutrition for present generations without compromising the environmental, social, and economic needs of future generations” (HLPE Food Security and Nutrition: *Building a Global Narrative towards 2030*. High Lev. Panel Expert. 2020, no date).

Thus, food security has prevailed as a global concern for decades, while agriculture has been a key tool for producing food to feed the world's population (Pawlak & Kołodziejczak, 2020). This is because plant-based foods contain several minerals, macronutrients (carbohydrates, lipids, and proteins), and micronutrients (vitamins A, B complex, C, E, and K) necessary for human nourishment (Roberts & Mattoo, 2019), which makes their consumption essential to ensure dietary requirements.

Main crops produced around the world include cereals (maize, rice, wheat, barley, and sorghum), representing 32% of total crop production; sugar crops (sugarcane, sugar beet), accounting for 22% of the total, vegetables (tomatoes, onions, cucumbers, cabbages, and eggplants) and oil crops (oil palm fruit, soya bean, seed cotton, colza seed, and coconuts) with 12% each; fruits (bananas, watermelons, apples, oranges, and grapes) and roots and tubers (potato, cassava, and taro) with 10% and 9% of the total global production, respectively (FAO FAOSTAT ANALYTICAL BRIEF 60, *Agricultural Production Statistics 2000–2021 FAOSTAT Analytical Brief 60 FAOSTAT CROPS AND LIVESTOCK PRODUCTION INTRODUCTION*. Agric. Prod. Stat, 2000; Food and Agriculture Organization of the United Nations FAOSTAT, 2024) (Fig. 15.1).

Agricultural production has achieved high yields due to the implementation of irrigation and the massive use of synthetic fertilizers and pesticides. By these means, primary crop production worldwide has reached about 9.5 billion tons per year in recent years according to the FAO (FAO FAOSTAT ANALYTICAL BRIEF 60, *Agricultural Production Statistics 2000–2021 FAOSTAT Analytical Brief 60 FAOSTAT CROPS AND LIVESTOCK PRODUCTION INTRODUCTION*. Agric. Prod. Stat, 2000). However, although intensive strategies have contributed to a huge increase in the obtained yields, they have also caused diverse negative impacts, such as the acidification and erosion of soils; a decrease in their fertility and microbial diversity; the generation of pesticide resistance; and the eutrophication of surface

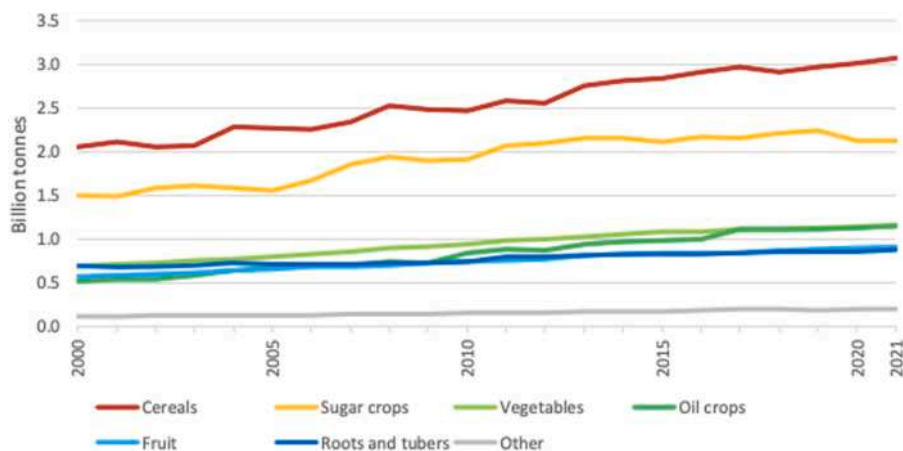


Figure 15.1 Global production of primary crops by the commodity group.

Taken from the FAO's Plant Production and Protection Division, 2022; Food and Agriculture Organization of the United Nations FAOSTAT, 2024.

waters, as well as contamination of groundwater, rivers, and the ecosystem in general (Clapp et al., 2022; Roberts & Mattoo, 2019).

Furthermore, to complement intensive agricultural practices, crop breeding design has been directed toward the improvement of qualities such as bigger and more abundant fruit, increased grain fill, and disease resistance. Thus, the designed cultivars from the last decades are rich in macronutrients like proteins, carbohydrates, and fats, but not in minerals and vitamins. Consequently, major food crops used at present are lacking important micronutrients. This aggravates due to the impoverishment of agricultural soils, which are currently depleted of essential minerals for the plant, decreasing their beneficial properties (Gaikwad et al., no date). Fortunately, at present, there is a focus on developing cultivars that meet both yield and nutritional qualities, together with resistance to biotic and abiotic stresses, as well as the improved utilization of water and soil nutrients (Roberts & Mattoo, 2019). For accomplishing this, optimized crop cultivation systems need to be implemented based upon the strategies for a more environment-friendly and consumer-oriented agriculture (Ingrao et al., no date).

Along with the technological challenges that undergo crops, multiple abiotic and biotic stressors have increased over time, especially due to climate change. Main abiotic factors include soil drought, temperature stresses, high salinity, UV-radiation, and heavy metal contamination, among others (Dhakal et al., 2021).

Global temperature is increasing continuously as a consequence of the accumulation of greenhouse gases (GHGs) in the atmosphere (mainly CO₂) and is estimated to rise around 2°C by 2100 (Malhi et al., 2021). This is provoking a climate change crisis, which is defined as significant variations in the temperature and precipitation average values (Malhi et al., 2021). For instance, the number and strength of storms

are predicted to increase, together with temperature and rainfall variability. These phenomena are exerting increasing pressures on agriculture worldwide, both for cereal and horticultural crops, causing, for example, higher evapotranspiration and a general decrease in crop yields and nutritional properties (Clapp et al., 2022). According to recent models, on high latitudes, such as North America and Eurasia, the crop yields are projected to increase, due to the increase in photosynthesis driven by carbon dioxide (CO₂) accumulation (Cai & Cao, 2022) (Fig. 15.2). However, this effect is prone to be countervailed by elevated temperatures and variable precipitations (Malhi et al., 2021). Moreover, in tropical regions, the impact of climate change will likely to reduce the production yields, especially for cereal crops; in drought regions, major crops are predicted to be reduced by 50% in 2050 and by 90% in 2100 (Malhi et al., 2021).

Furthermore, pathogenic infection risk is predicted to increase as well, for as climate changes, suitable conditions for plant pathogenic outbreaks shift of season and the affected region, which increases the regions where pathogens can develop and from they were absent before, leading to the emergence of new pathogens and diseases (Chaloner et al., 2021).

Biotic stressors consist mainly of plant-pathogenic organisms such as insects, nematodes, viruses, bacteria, and fungi (Parmar et al., 2017). Plant pathogens are one of the main threats to crops worldwide as they can cause up to 50%–75% of yield

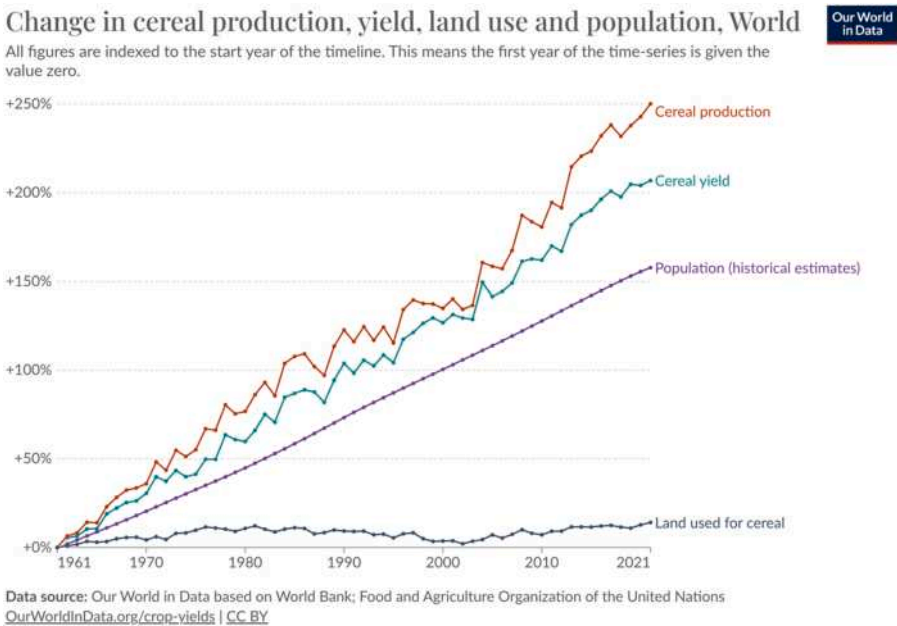


Figure 15.2 Change in cereal production, yield, land use, and population worldwide (Ritchie et al., 2024).

losses in diverse crops such as wheat, maize, vegetables, fruits, and ornamentals and are the cause of about 90% of the current plant diseases (Panth et al., 2020). For this reason, most efforts are destined for the management of biotic stressors, which sometimes provoke bad agricultural practices and the unrationalized application of agrochemicals. These practices, in addition to damaging the ecosystem, have become unsustainable due to the generation of resistance by pathogenic species.

The sustainability concept has thus become fundamental to ensuring food security for the upcoming generations. Indeed, the world population is estimated to reach nearly 10 billion people in the next decades, which implies the need to increase crop yield production around the globe to maintain food security worldwide. Hence, the search for sustainable agricultural practices is one of the main concerns for modern food systems. A promising tool for the regeneration of agricultural soils is the use of next-generation microbial inoculants, which have proven to increase crop yields by improving water and nutrient utilization (Ayala Zepeda et al., 2024). Furthermore, several beneficial microorganisms have been used as biological control agents for numerous plant pathogens due to their strong antagonistic properties (Montoya-Martínez et al., 2023; Valenzuela-Ruiz et al., 2022).

Thus, this book chapter presents the various consequences of climate change on the abiotic and biotic factors affecting diverse cereal and horticultural crops, as well as the innovative strategies that are being developed around the world to mitigate those stresses and the recent focus on maintaining and/or regenerating the microbial diversity of soil. The reported benefits of these practices include soil health increase, thus becoming a better source of nutrients for plant development, as well as a better utilization of the applied nutrients.

15.2 Factors affecting food security around the world

The ability of agriculture to meet the demand for food is hindered by adverse conditions during crop production, mostly due to unfavorable environmental factors and the proliferation of pests and diseases in plants. As previously mentioned, food security presents a global challenge, and climate change increases threats from both biotic and abiotic factors. Hence, it is imperative to identify how diverse factors endanger agriculturally significant crops and how to mitigate their impact.

15.2.1 Abiotic stress

Abiotic stress refers to environmental factors that exert negative impacts on plants, resulting in changes that disrupt their metabolic and/or physiological processes, ultimately leading to reduced yields (Zhang et al., no date). Some of these factors include alteration in climate patterns (e.g., extreme heat, drought, frost, floods), as well as soil degradation (e.g., erosion, salinity, compaction) and its low availability of nutrients. These agents are an important source of severe problems and in 50%–82% of the cases lead to irreversible effects on cultivated lands, ultimately impacting crop production and quality (Imran et al., 2021). In this section, some of these problems will be thoroughly described.

15.2.1.1 Alterations in climate patterns

Since the 19th century, the global temperature has increased by 0.9°C, primarily due to the emission of GHGs (Pachauri & Meyer, 2014). Some natural phenomena cause temperature changes on the Earth; however, the temperature increase is mainly the result of anthropogenic activities that lead to the emission of CO₂, methane, nitrous oxide, and other ozone-depleting substances (Montzka et al., 2011). Estimates suggest that, if tendencies do not change, by 2050, this temperature rise will reach approximately 1.5°C or even higher which could have dreadful impacts on diverse ecosystems.

Climate change alterations modify long-term trends in temperature and precipitation, as well as other components such as ambient pressure and humidity levels. In addition, erratic weather patterns, retreating global ice sheets, and the resulting sea level rise are some of the most extreme effects of climate change (Abbass et al., 2022). The projected impacts of climate change on soil are multifaceted, including the physical changes, like increased water and wind erosion, and a loss of structural integrity (Eekhout & de Vente, 2022). Biological effects, on the other hand, manifest mainly as a significant reduction in biodiversity (Habibullah et al., 2022). There are also expected to be biochemical disruptions, alongside chemical degradations, that could affect essential biogeochemical cycles (Abbass et al., 2022). This degradation is likely to result in a decrease in organic matter and lead to issues such as acidification, salinization, and sodification of soils (Mukhopadhyay et al., 2021).

Agriculture stands as one of the activities more susceptible to climate change, due to plants' sensitivity to weather conditions, resulting in substantial economic repercussions worldwide (Mendelsohn, 2008). A decline in crop yields can escalate food prices and profoundly impact global food security, affecting the food availability, quality, accessibility, and utilization, as well as the overall stability of food networks (Eftekhari, 2022).

Even though temperature increase is one of the most critical factors during climate change, water scarcity is one of the most worrisome consequences nowadays. The shortage of this vital resource generates intense droughts that lead to yield losses in crops, which commonly vary between 30% and 90%, with differences being observed among the crop species (Mendelsohn, 2008). The unpredictability of rainfall patterns and the increment in the occurrence of droughts and floods are anticipated to cause a notable reduction in crop yields across numerous regions (Perspectivas Mundiales & Organización de Las Naciones Unidas Para La Alimentación y La Agricultura Available online, 2024). This susceptibility is attributed to the fact that the plant–water relationships are highly sensitive to climate change (Reyer et al., 2013). Physiological traits, such as the root elongation, alterations in the root growth angle, and yield reduction, are influenced by these extreme variations. However, these impacts also vary among different plant species (Gray & Brady, 2016).

15.2.1.2 Soil degradation

A recent definition of soil describes it as the layer(s) of generally loose mineral and/or organic material that is affected by physical, chemical, and/or biological processes at

or near the planetary surface; it usually holds liquids, gases, and biota and supports plants (van Es, 2017). Thus, preserving soil health is crucial, as it provides the supply (such as food, feed, and fiber), regulation (including the climate control, soil erosion, and water purification), and support (like nutrient cycling and soil formation) for the agricultural activities that provide food security (Schreefel et al., 2020).

The main factors that generate soil degradation include soil compaction, soil salinization, and soil erosion (Fig. 15.3), with soil erosion being of the most concerning factors (Ferreira et al., 2022). It consists of the decomposition and transport of soil particles by erosive agents (Lal, no date), these include water, wind, and gravity. Nevertheless, water is the principal eroding agent, responsible for 56% of all global losses due to soil erosion (Bouma & Batjes, 2000). It should be noted that erosion is a natural process that results in the formation of new soils; however, this process takes millions of years. What is commonly described as a problem, is due to the accelerated erosion caused by anthropogenic activities, such as deforestation or intensive agricultural practices (Nasir Ahmad et al., 2020).

Erosion mainly affects the fertile layer on the soil surface, which plays a crucial role in the productivity of agricultural and natural ecosystems (Eekhout & de Vente, 2022), as most of the soil organic matter is located at this layer (Pennock, 2019). Thus, erosion generates three main problems: (1) it removes the fertile layer of the soil; (2) it incorporates part of the dense subsoil to the surface, and (3) it generates an impediment to crops' root development (Van Oost et al., 2009), all of which affects the soil biodiversity and disturbs biogeochemical cycles (Ferreira et al., 2022).

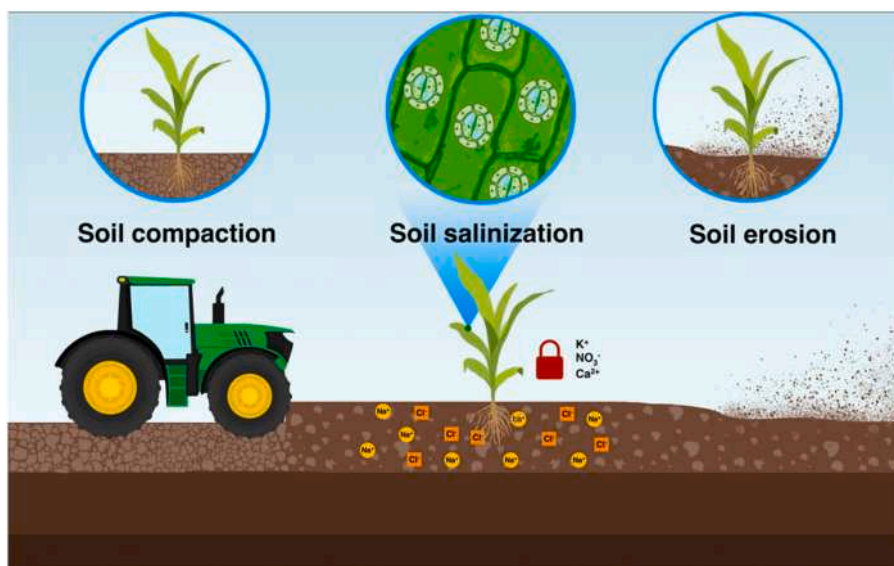


Figure 15.3 Main factors generating soil degradation in croplands.

Furthermore, according to recent predictions, each 0.1 m of soil loss may cause a 4% yield decline in crop production (Quinton et al., 2010).

Agriculture, like other activities, has a strong impact on soils, and although this sector is greatly affected by the consequences of erosion, it is also one of the main causal agents for this problem. Ten years ago, it was estimated that 80% of the land dedicated to agriculture was moderately to severely eroded (IAEA Guidelines for Using Fallout Radionuclides to Assess Erosion and Effectiveness of Soil Conservation Strategies, 2014). In the European Union (EU), for instance, 60%–70% of soils are currently degraded, which causes them to lose their capacity to provide vital ecological functions for the organisms that develop on them (Veerman et al., 2020). This implies that approximately 75 billion tons of arable soil are lost worldwide, generating losses of \$400 billion in agricultural production (FAO Global Soil Partnership Endorses Guidelines on Sustainable Soil Management et al., 2024). Even, when in 2012, the cultivated soil cover was about 11% of the studied land, and agriculture was responsible for about 50% of the total soil erosion, being about 77 times higher than the natural erosion in forests (Borrelli et al., 2017). This eroding percentage is expected to keep increasing unless there is a significant change in current agricultural practices.

On the other hand, soil compaction is another problem that generates soil degradation (Ferreira et al., 2022). This stress involves densification and deformation of the soil under tensions greater than its strength, which is mainly caused by intensive agriculture during the use of heavy machinery (Jamali et al., 2021). Over the last 60 years, this machinery has immensely increased its weight, which directly correlates with a significant increase in soil compaction (Keller et al., 2019). The effects of compaction have been reported to reduce crop yields by 10%–15% (Godwin et al., 2019). However, in crops like cotton, it has been reported that yield reduction can reach up to 27% (Jamali et al., 2021). This is because the compaction of soil affects its physicochemical properties, causing low porosity, disrupted pore continuity and connectivity, and increased soil obstruction (Shaheb et al., 2021), thereby generating issues with water and nutrient absorption by crops. Consequently, roots experience delayed lateral growth and fail to develop deep root systems (Liu et al., 2022). This stress also has a direct impact on soil salinization because it reduces its permeability, causing the concentration of salts in the outer layer of the soil as water evaporates (Hassani et al., 2021).

It is important not to confuse soil salinity and soil salinization. Soil salinity refers to the concentration of salts in the soil (Kumar & Sharma, 2020) and is categorized based on the pH of saturated soil paste, the electrical conductivity of saturated paste extract (EC_e), and the exchangeable sodium percentage (Machado & Serralheiro, 2017). Meanwhile, soil salinization is the process of salt accumulation, and these saline soils are classified into three groups: saline soils, alkaline soils, and saline–alkaline soils (Mukhopadhyay et al., 2021). Around 85% of soil around the world is slightly or moderately impacted by high salinity while the remaining 15% has a severe problem of salt concentration (Kumar & Sharma, 2020).

Even though there are natural processes of soil salinization (primary salinization) like rainfall, eolian processes, and weathering of parent rock materials (Hassani et al., 2021);

excessive accumulation of soluble salts in the soil can be caused by anthropogenic activities (secondary salinization). These activities include the overuse of agrochemicals, the use of water effluents, and land clearing for cultivation, which have strong implications for the productivity and quality of the crops (Singh, 2022). They generate economic losses of around 27.3 billion dollars per year due to not marketable fruits, roots, tubers, and leaves (Qadir et al., 2014). Some statistics estimate that 20% of total cultivated lands and 33% of irrigated agricultural lands worldwide are afflicted by high salinity (Shrivastava & Kumar, 2015) and around 52 million ha of lands are affected by salinization in South Asia (Kumar & Sharma, 2020).

Saline soils affect the development of plants due to increased osmotic pressure in the soil and its interference with plant nutrition, which in turn reduces the plant's ability to acquire water (Machado & Serralheiro, 2017). Saline stress also affects the photosynthesis process, generating a reduction in the content of photosynthetic pigments, and limiting plants' growth capacity. At the same time, the high concentration of Na^+ and Cl^- ions have specific toxic effects on plants (Shrivastava & Kumar, 2015) and inhibit the absorption of other important nutrients for the plant, such as K^+ , NO_3^- , and Ca^{2+} (Paranychianakis & Chartzoulakis, 2005).

15.2.2 Biotic stress

Besides the abiotic factors described above, plants are subjected to numerous biotic threats, such as weeds, insects, viruses, pathogenic bacteria, and fungi, among others (Malhi et al., 2021). Direct yield losses caused by pathogens, pests, and weeds are estimated to reach about 20%–40% of crop production, which represents a strong negative impact on crop productivity and thus an important threat to food security (Savary et al., 2012). Due to the inadequate use of agrochemicals, which generate pest resistance, an alarming increase in the number of transboundary pathogens has been reported, as well as the emergence of new diseases linked to climate change (Varshney et al., 2011).

Throughout history, agricultural systems have played a pivotal role in shaping ecosystems' biodiversity (Woodbridge et al., 2023). For instance, Insects thrive in regions with extensive monocultures and intensive fertilizer application (Oerke & Dehne, 2004). Every year, pests alone inflict damages amounting to at least 70 billion USD worldwide (FAO FAO's Plant Production and Protection Division, 2022). In addition, climate change and weather anomalies directly affect insects' population dynamics by influencing their reproduction, development, survival, and dispersal. Indirectly, climate change modifies interactions both between and within insect species; altering relationships with predators, competitors, and mutualists, as well as their interactions with the environment (Subedi et al., 2023). Because insect body temperature depends on the environment, elevated temperatures can enhance insect feeding, performance, and dispersal (González-Tokman et al., 2020), potentially increasing the number of generations of insects per growing season (Skendžić et al., 2021; Subedi et al., 2023).

The indiscriminate use of pesticides has generated a threat to nontarget organisms (Serrão et al., no date), which is not desirable as insects not only act as pests but also

play vital roles in ecological functions (Jankielsohn, 2018). For instance, some insects, such as moths, hoverflies, bees, butterflies, wasps, thrips, and beetles, contribute to pollination (Khalifa et al., 2021). They are also involved in predation and parasitism, such as *Trichogramma* spp., and insects from the family Chrysopidae (Martel et al., 2021), which have been used as pest controllers (Ghongade & Sangha, 2023). Additionally, insects like beetles (Coleoptera, Scarabaeoidea) play a significant role in biodegradation, acting as important decomposers and contributing to nutrient recycling and plant productivity (deCastro-Arrazola et al., 2023). Therefore, the rationalized application of pesticides is essential to strike a balance between minimizing both yield losses and environmental impacts on beneficial insect populations. Furthermore, biotic stresses for plants are caused by parasites, such as nematodes, which are responsible for significantly greater annual damage than insect pests. According to estimates, these invisible pests cause a crop yield loss of about 12%, equivalent to 157 billion dollars. India alone has reported losses of \$40.3 million due to nematodes (Singh et al., 2015). When nematodes attack the roots, they disrupt water translocation to the aerial parts of the plant and divert nutrients to themselves. This leads to underdeveloped plants with stunted growth, chlorosis, yellowing, and leaf loss, ultimately resulting in reduced crop yields and can also act as virus vectors, affecting the beneficial microbiota of the plant (Ali et al., 2017).

One of the best-known examples of this parasitoid activity is the root-knot nematode, *Meloidogyne* spp. and cyst nematodes (CNs), *Globodera* spp. and *Heterodera* spp. The species of the genera *Meloidogyne* affects a wide selection of crops, however, from an economic point of view, the most important are soybean, cereals, tomatoes, potatoes, and other solanaceous and tuberous crops (Tapia-Vázquez et al., 2022). In tomatoes alone, yield losses ranging from 10% to 80% caused by this nematode have been reported (Seid et al., 2015). On the other hand, CNs are a common problem in potato crops, caused by *Globodera pallida* and *G. rostochiensis* (Varandas et al., no date). Controlling these parasites is challenging because they protect themselves by producing a cyst during their early life stages. Moreover, they are capable of surviving in the soil for more than 20 years without a host plant. Seed potato-producing countries experience a major economic impact, with an estimated 9% of total global production losses attributed to nematodes (Turner & Rowe, 2006). Another important biotic source of stress for agriculture is plant pathogens. Among these, bacteria, fungi, and viruses have been identified as the primary agents responsible for causing plant diseases (Gimenez et al., 2018), which constitute a significant challenge to the agricultural sector (Kathole et al., 2023).

Bacterial plant diseases are mainly caused by six genera of bacteria: *Erwinia*, *Agrobacterium*, *Corynebacterium*, *Pseudomonas*, *Streptomyces*, and *Xanthomonas* (Michalak et al., 2021). Of the genus *Erwinia*, the species *Erwinia amylovora*, develops the disease known as Fire Blight (FB) (Paraschivu et al., 2022) and it is probably the most destructive bacterial disease in apple and pear orchards worldwide (Gusberti et al., 2015). *Agrobacterium* is a genus mostly known for its biotechnological applications; however, it also possesses pathogenic activity. Within this genus, there are several pathogenic species: *A. rhizogenes*, which causes hairy root disease; *A. rubi*, responsible for cane gall disease; *A. vitis*, which leads to grape crown gall; and *A. tumefaciens*, associated with crown gall disease (Otten et al., 2008). Lesions caused by these

pathogens can serve as sites for secondary infections by other plant pathogens, such as *Pseudomonas syringae* and *Armillaria mellea*, as well as for pests insects (Escobar & Dandekar, 2003). *P. syringae* is one of the most common plant pathogens that infect plant phyllosphere using a variety of virulence factors (Xin et al., 2018). There are more than 60 pathovars that have been identified in this bacterium species, with each pathovar (pv) infecting more than 180 specific host plants, significantly threatening global crop production (Córdova et al., no date; Popović et al., 2021). The most common diseases caused by *P. syringae* include the bacterial canker disease in cherry, apple, plum, peach, and kiwi (Ilicic et al., 2023; Marroni et al., 2024; Narouei-Khandan et al., no date) apical necrosis of mango (Gutiérrez-Barranquero et al., 2019); a speck in tomato plants (Butsenko et al., 2020) and the brown spot of beans (Fernández-Sanz et al., 2020).

Phytopathogenic fungi represent the most serious biotic threat to crop yields and staple foods upon which the population relies and therefore to food security (Steinberg & Gurr, 2020). Due to the impact of agricultural systems and intensive practices on pathogen evolution, there is a rise in emerging fungal and oomycete pathogens (Fones et al., 2020). For instance, rice (*Oryza sativa* L) is a major cereal crop that feeds half of the world's population. However, it is increasingly threatened by fungal pathogens such as *Magnaporthe oryzae*, *Fusarium* spp., and *Rhizoctonia solani*, which are the causal agents of diseases like rice blast, rice seedling blight, rice bakanae, and rice sheath blight (Khaskheli et al., 2020). Phytopathogenic strains of *Fusarium*, including *F. graminearum* and *F. oxysporum*, rank among the top five fungal pathogens (Sharma & Marques, 2018) affecting plants and causing billions of dollars in losses per year globally (Bakker et al., 2018). The *F. graminearum* species complex affects wheat, barley, oats, and corn and causes a variety of diseases including seedling blight, root, and crown rot, as well as fusariosis in cereal grains (Chaves et al., no date). The *F. oxysporum* complex has been reported to cause wilt in peppers (Montoya-Martínez et al., no date).

Another important biotic stressor is weeds, known as extreme environmental stress tolerators due to their resistance to extreme environments (Chen et al., no date). Weed infestation of crops is also predicted to increase with the accumulation of atmospheric CO₂ (Malhi et al., 2021). Weeds cause important yield losses, such as in the case of sugarcane in which weeds reported losses of 0.1–0.2 Mg ha⁻¹ d⁻¹ (Soulé et al., 2024). Weeds interfere with crops' photosynthetic capabilities, even when they do not directly shade the crops, also competing for plant resources. Their preventive control is preferred as weeds that emerge earlier than the crop will significantly impact production yields, whereas those that appear during the later stages of crop vegetative growth have minimal effect on yield, even when they grow taller than the crop (Horvath et al., 2023).

15.3 Environmental consequences of climate change

Efforts are made around the globe to reduce the impact of climate change and the increase in the occurrence of extreme weather events. The objective is to stay within a threshold that does not exceed a 1.5°C increase in temperature, since above this change permanent and irreversible changes on the planet will be generated (Nguyen

et al., 2021) (Fig. 15.4). An important factor contributing to global warming is the emission of GHGs by anthropogenic activities, such as industrialization (Adedoyin et al., 2020; Pata, 2018). In the last three centuries, there has been a major accumulation of GHG in the atmosphere; methane (CH₄), CO₂, and nitrous oxide (N₂O) have augmented by 150%, 40%, and 20%, respectively, CO₂ being the most abundant of the three (Malhi et al., 2021). This buildup of GHG causes a reemission of radiation to the Earth that increments the global temperature (Méndez-Cadena et al., 2020). This threatens both the sustainability of the Earth and the survival and development of humanity, because it directly affects the availability of water (which mainly harms agriculture), contributes to air pollution (shortening the lifespan of living beings), and increases the intensity of sunlight due to the thinning of the ozone layer (Adedoyin et al., 2020; Chu et al., 2017).

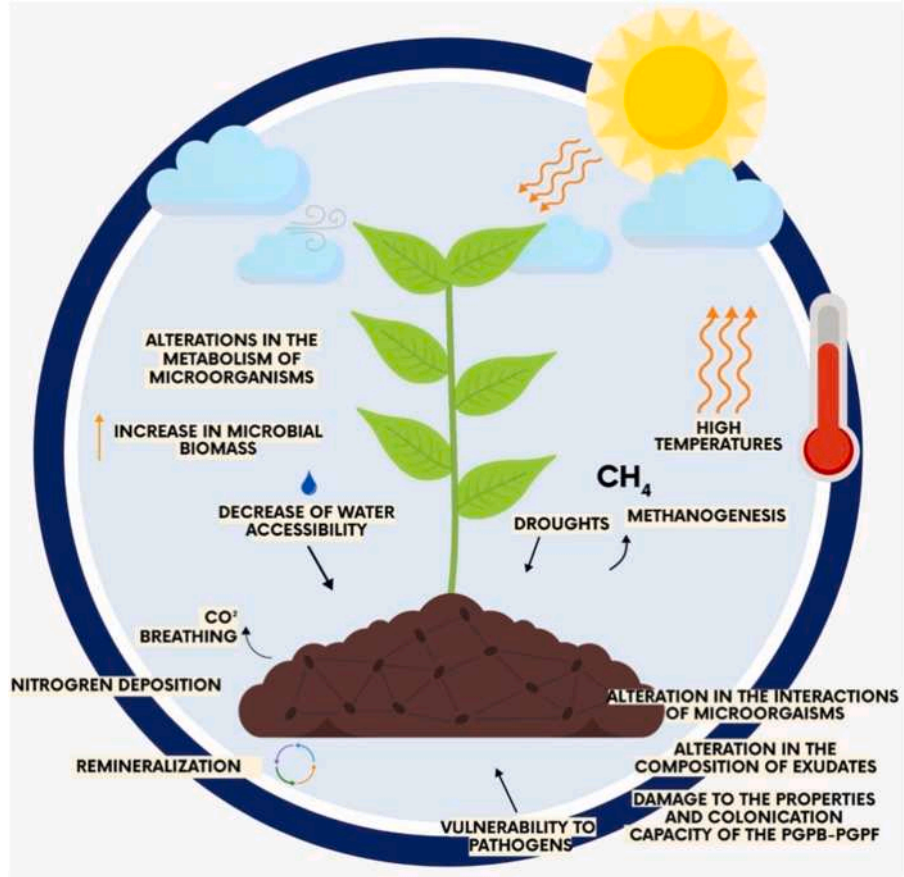


Figure 15.4 Consequences of environmental stressors on plant development.

As mentioned above, climate change directly impacts crops by causing an increase in droughts, heat waves, and abiotic stress conditions such as flooding, salinity, and freezing stress (Zandalinas et al., 2021). In addition to increasing biotic and abiotic threats that directly affect crops, climate change has various environmental consequences that indirectly impact agriculture. The combination of three or more factors that simultaneously affect plants is known as the multifactorial stress (Zandalinas et al., 2021).

An increase in environmental temperature caused by global warming is one of the most important factors affecting the abundance distribution of plants, due to the physiological limits of the species. It is a factor that limits the places where plants are grown, as extremely low and high temperatures can have detrimental effects on the rate of development, growth, and yield of crops (Parmesan & Yohe, 2003; Skendžić et al., 2021). These temperature variations are generally associated with environmental factors such as the availability of water, the appearance of strong winds, and the intensity and duration of sunlight. For example, rising temperatures come with a greater demand for atmospheric water, which causes additional water stress due to water pressure deficits, which would subsequently end up reducing soil moisture and yield (Skendžić et al., 2021; Zhao et al., 2017).

The magnitude of hydrological changes attributed to climate change remains understudied, as water levels are affected by climate change through a complex network of forces linking surface temperature to hydrology (Rodell et al., 2018). The accessibility to water resources for human consumption and ecosystems depends on the distribution of both evaporation and precipitation. As a result of climate change, variations in precipitation and evaporation patterns directly result in the modification of water availability, which has implications for both humans and the biosphere (Konapala et al., 2020). Warming has been observed across the Earth's surface; however, hydrological responses to warming vary, with some areas becoming wetter and others drier (Greve et al., 2014; Kraemer et al., 2020). For example, an increase in the seasonal variability of precipitation would alter the continuous supply of concentrated water in the atmosphere, leading to prolonged dry periods in certain regions, and, in regions with high precipitation, this redistribution would result in a greater concentration of water in a short period, which would cause flooding (Konapala et al., 2020).

Thus, water represents another crucial component affected by climate change, as environmental conditions influence the demand, availability, and quality of this resource, impacting the global hydrological cycle (Naqvi et al., 2015). Furthermore, changes in temperature and climate affect also the quantity and distribution of precipitation worldwide. Hence, inadequate water management and the consequent lack of this resource in some world regions represent a risk to sustainable agriculture, impacting economic, social, and environmental stability (Naqvi et al., 2015).

Moreover, it has been reported that extreme climatic variations are commonly accompanied by a decrease in soil microbial diversity (Rillig et al., 2019). Plant life, microbiomes, and soil health are likely to deteriorate due to the increasing number of environmental stressors occurring simultaneously on croplands. If the disruption to climatic conditions and environmental pollution continues, it could lead to an even

greater decline in soil microbial diversity, which hinders plant growth and overall agricultural productivity (Zandalinas et al., 2021). If soils become more arid, the challenge for the agricultural sector increases, as the soil microbial communities play a crucial role in ensuring nutrient availability for plants' development, meaning that the general agricultural capacity of producing enough food for the world population will be at risk (Lozano-Povis et al., 2021).

15.4 Impact of climate change on microbiome and plant diseases

As mentioned before, microbial diversity is responsible for sustaining essential functions and exchanges in natural ecosystems, promoting their stability by mediating diverse biogeochemical cycles. Understanding the impact of climate change on soil microbiomes and their enzymatic activities, represents a major challenge for researchers and a great opportunity to improve their use toward solving one of the most pressing issues of our time, feeding the population (Jansson & Hofmockel, 2020).

Plants are closely associated with diverse microbial communities which contribute to their capacity to resist environmental stress and to endure environmental perturbations, such as the ones caused by global warming (Trivedi et al., 2020). These complex and dynamic interactions between plants and the soil microbiome are strongly influenced by the environment (Trivedi et al., 2020). With climate change, many plant communities are enduring rapid and significant fluctuations in temperature, precipitation, evaporation patterns, and their associated environmental phenomena, such as droughts and floods. These factors cause modifications in the current geographical distribution and optimal conditions for crops, as well as to their associated microorganisms, both beneficial and pathogenic (Burdon et al., 2020).

Although the impacts of climate change are widespread, they are not uniform, as they vary depending on exposure, vulnerability, sensitivity, and adaptive capacity of the microbiome (Beever et al., 2016; Kovach et al., 2019; Weiskopf et al., 2020). However, it has been reported that the changes at the population and species level may result in a response to climate change (McCann et al., 2018). It is estimated that by the year 2100, there will be a temperature increase of 3.5°C; as soil microbial communities are already being influenced by climate change, the increase in temperature represents an inevitable and irreversible impact on the ground microbiome. Therefore, it is important to understand the response of soil microorganisms to the diverse consequences of climate change to improve prediction models and mitigate the potentially adverse effects.

Reciprocally, soil microbiome influences ecosystem health by modifying carbon sequestration during the mineralization of soil organic carbon (SOC) (Naylor et al., 2020). The total amount of soil carbon is estimated to be approximately five times greater than the current atmospheric reserve of CO₂ (Cavallaro et al., 2018; Jansson & Hofmockel, 2020). Furthermore, the nitrogen cycle mediated by microorganisms can also be affected due to global warming (Frey et al., 2014; Naylor et al., 2020). Atmospheric nitrogen deposition is projected to increase two to threefold in the next century (Yu et al., 2019). It is widely recognized that increasing nitrogen deposition rates will lead to soil acidification,

altering the nitrogen availability of soil nutrients and a general modification in the composition of microbial communities (Yang et al., 2020).

15.4.1 Modification of microbiome diversity

Soil is one of the most diverse ecosystems on our planet, with an interactive community of bacteria, archaea, viruses, fungi, and protozoa known as the “soil microbiome.” When soil abiotic factors combine with microbial activity, the soil environment becomes very dynamic. However, due to climate change, extreme changes are being introduced that lead to unknown consequences on the stability and resilience of the soil microbiome (Jansson & Hofmockel, 2020). Because soil properties vary in their biotic and abiotic properties, it is difficult to generalize the nature of the impact of climate change on soil microbiomes as in some cases, microbiomes may benefit from specific variations. For instance, elevated CO₂ may lead to an increase in belowground carbon concentration as a result of increased plant growth, which in turn will contribute to soil microbial community mass growth (Allison et al., 2010; Yang et al., 2021). The enhancement of microbial activity and their rate of nutrient metabolism will lead to a faster SOC decomposition and further changes in bacterial/archaeal composition, as well as a decrease in the abundance of fungi (Naylor et al., 2020; Wang et al., 1987). However, previous investigations have indicated that the warming of the environment and reductions in soil moisture exert a predominant detrimental influence on the configuration of microbial biodiversity, as they result in a decrease in the richness of bacteria (9.6%), fungi (14.5%), and protists (7.5%) (Wu et al., 2022). Moreover, climate change may lead to different pathogenic species expanding their range and being able to colonize new environments where they could not previously survive or, in some cases, to a reduction in their range due to increased biotic and abiotic stressors. Furthermore, the transfer of microbiomes occurs both within and between abiotic and biotic environments. These transfer processes also encompass the transmission of pathogens or resistance genes (Sessitsch et al., 2023).

Numerous interactions between the microbiomes and plant hosts of different agricultural systems remain largely unknown. However, it has been established that there is a generalized impact on the whole system when a parameter gets modified, due to their interconnections and exchange of information between them (Schmeller et al., 2020). The impact of climate change on the diversity and abundance of soil microbial communities has yet to be fully resolved.

15.4.2 Occurrence of emerging pathogens

A plant pathogen can be classified as emergent if (1) it causes a new disease; (2) it greatly increases the incidence of an existing disease; (3) it introduces a disease to a new geographic location; or (4) it acquires the capacity to infect a new host (Fisher et al., 2012). There are different ways in which a disease arises: the pathogen can be introduced into a new area where its host is located by physical transport or by the development of permissive abiotic factors (e.g., climate or atmospheric composition) (Fones & Gurr, 2017); or on the other hand, the host may be the one who enters the area where the pathogen is present. Emerging infectious diseases can be defined as diseases that prevail over time, including new unknown diseases that are diagnosed

for the first time and/or old diseases that have evolved (El-Sayed & Kamel, 2020). Temperature is a determining factor in disease risk and the global distribution of pathogens has changed by the planet's historical global warming (Chaloner et al., 2021).

There is a complex community dynamic between the environment, plants, beneficial microorganisms, and pathogens during natural interactions. Those relationships need to be further studied to regulate pathogenic outbreaks while maintaining the biodiversity of natural communities (Burdon et al., 2020). Like all species, crop pests and pathogens have particular requirements that define their ecological niche and determine the geographic regions and periods of the year that allow them to proliferate and attack crops. As climate change occurs, the conditions suitable for pest and pathogen outbreaks change over time, thus altering the threats facing the agricultural sector and the regimes necessary for their control (Chaloner et al., 2021). Furthermore, plant infection and disease manifestation are determined by complex and species-specific interactions between various biotic and abiotic factors. The alterations caused by climate change have favored diverse aspects for pathogenic microorganisms, including greater suitability of climatic conditions for their reproduction, acceleration of their lifecycle, increase in seasonal occurrence and duration of exposure, as well as facilitating their virulence (Mora et al., 2022). In addition, as microorganisms can acquire genes through mutation, hybridization, or horizontal gene transfer, the genes that confer greater virulence can be transmitted between pathogenic strains, thus allowing infection of a new host or resistance to disease control measures (Fones et al., 2020).

Climate change produces a confluence of factors that can act together to promote the emergence of new pathogens (Nnadi et al., 2021). For this reason, it is essential to regularly monitor the microbial species present on agricultural fields to timely detect the outbreak of new diseases and/or the significant increment in recurrent pathogenic strains. An important key to effectively managing crop diseases is to prevent their dispersal by acting on the early stages of their development. To facilitate this task, there exist nowadays innovative genomic techniques for detecting, identifying, and tracking known pathogens, allowing the surveillance of the spread of plant diseases. These techniques rely primarily on high-throughput DNA sequencing technologies to rapidly sequence and analyze pathogenic genomes. Researchers can therefore determine the origin of an outbreak, trace its transmission patterns, and monitor the evolution of the pathogen over time (Vashisht et al., 2023).

15.5 Current and innovative strategies to mitigate plant stress

To face the numerous agricultural challenges listed before, it is important to mention the various strategies that are being employed to mitigate these stressors and increase crop productivity, as well as their advantages and disadvantages. Moreover, it is essential to explore innovative alternatives, that are more environmentally friendly and lead to increased sustainability in agricultural practices. Here, we enumerate

several strategies for combating biotic stressors and improving crop yields, both traditional and innovative, as well as their benefits and inconveniencies.

15.5.1 Agrochemical pesticides and fertilizers

As mentioned before, damage caused by agricultural pests and diseases is a critical limiting factor for global food production. Modern agroindustry relies on the use of agrochemicals to mitigate those losses, allowing a major improvement in crop yields for the last 50 years (Himani et al., 2022; Lamberth et al., 2013). Thus, agrochemicals are compounds used in agriculture to improve crop yield and quality; the main compounds utilized include pesticides, fertilizers, plant growth regulators, and soil conditioners (Himani et al., 2022). Synthetic pesticides are used to control pests and plant diseases (Abdollahdokht et al., 2022). They can be classified based on their target as insecticides, herbicides, fungicides, rodenticides, bactericides, and nematocides (Abdollahdokht et al., 2022; Himani et al., 2022). Some of them will be detailed below, along with their mechanisms of action, as well as their main advantages and drawbacks. Synthesis is also presented in Table 15.1.

For instance, insecticides are chemical compounds destined to kill, repel, and control damaging insect pests. They penetrate the insect’s body through ingestion,

Table 15.1 Advantages and disadvantages of diverse strategies for stress mitigation in crops.

Strategy	Advantages	Disadvantages
Agrochemical pesticides	• Increase in crop yield. • Almost immediate results. • Cheap/cost-effective.	• Risk to human health. • Water and soil contamination. • Loss of biodiversity. • Risk of resistance by the targets.
Biotechnologically modified plant-resistant varieties	• Higher crop yields. • Decrease in the use of agrochemical pesticides. • Reduce carbon dioxide emissions. • Higher farmer and producer income.	• Concerns about biosafety issues, resistance breakdown, and adverse effects on nontarget organisms. • Elevated cost for commercialization. • Oligopoly of multinational companies.
Plant-growth-promoting microorganism (PGPM)-based bioinoculants	• Cheap to produce. • Eco-friendly and sustainable. low-input and time-saving compared to the development of resistant varieties.	• Ineffective or inadequate formulation. • Short shelf life. • Slow response compared with agrochemicals.

inhalation, or contact and cause its death by acting in three targets of their nervous system: acetylcholinesterase, which is an essential enzyme in nerve impulse transmission of insects (i.e., organophosphates and carbamates); voltage-gated Na⁺ channels across the nerve membrane (i.e., pyrethroids and dichlorodiphenyltrichloroethane known as DDT); and the acetylcholine receptor (neonicotinoids) (Abdollahdokht et al., 2022; Oberemok et al., 2015).

Other widespread agrochemical compounds are herbicides or weed killers, which are used to control unwanted plants (weeds), as they interfere with the growth of important crop plants and cause significant problems for farmers (Vats, 2015). There is a wide variety of herbicides available in the market, and they usually fall into one or more of the following categories: (1) growth regulators that mostly affect growth hormones and obstruct weeds' root and shoot growth (Zagnitko et al., 2001); (2) inhibitors of photosystem I and II, which include those that hinder the photosynthetic pathway of weeds, disrupting the electron transport system in the chloroplast or generating superoxide radicals and damaging the plant cell membranes (Vats, 2015); (3) lipid biosynthesis inhibitors, that block the production of lipids and fatty acids, turning the plants brown and killing them; (4) amino acid biosynthesis inhibitors, that inhibit the 5-enolpyruvylshikimate 3-phosphate synthase, glutamine synthetase or the acetolactase synthase (Zhang et al., 1999); and finally (5) inhibitors of the biosynthesis of pigments, such as chlorophyll and carotenoids (Abdollahdokht et al., 2022; Vats, 2015).

As previously stated, fungal diseases are one of the major causes of yield losses in agriculture, as phytopathogenic fungi can infect plants at any stage of development, obstructing their growth and, in some cases, causing their death or a major decrease in their production amount and quality. As the threat of fungal diseases increases with climate change, the necessity to effectively manage this risk becomes critical (Garrett et al., 2021; Tleuova et al., 2020). For this reason, a great number of agrochemicals are destined for the mitigation of fungal pathogens. Therefore, fungicides help to protect plants against fungal diseases by killing or stopping the development of fungal pathogens (Tleuova et al., 2020), this helps to prevent crop damage and increase agricultural production. There are several modes of action involved in the fungicidal activity, such as (1) the inhibition of ergosterol biosynthesis, which is one of the main components of fungal cell membrane structure, this group of fungicides inhibits the C14-demethylation during the ergosterol biosynthesis (i.e., imidazoles, pyrimidines, triazole) (Berg et al., 1986); (2) the inhibition of protein biosynthesis, by modifying the sulfhydryl groups of proteins (Jastrzębowska & Gabriel, 2015); and (3) the inhibition of mitochondrial electron transport, which inhibits mitochondrial respiration at the Qo site of the cytochrome b, which in turn hinder the spore germination and mycelial growth (Krämer et al., 2012).

Thus, agrochemicals have been key elements in agriculture production for decades, particularly pesticides that protect plants against biotic stresses, as they minimize the damages caused by pests and diseases, increasing crop productivity and quality (Babafemi et al., 2022). Furthermore, agrochemicals have also allowed broadening the range of viable crop options that a farmer can grow at particular times of the year, and it has been estimated that considerable economic losses would be suffered

without agrochemical use. They also allow for the reliability of production, which is economically important to any producer and farmer, by reducing the risk of catastrophic losses to pests and diseases (Cooper & Dobson, 2007). Besides, due to the use of agrochemicals, crops have maintained high yields for decades, thanks to which the cost of produce and food can be kept at relatively low prices for the final consumers (Saeedi Saravi & Shokrzadeh, 2011).

However, despite having numerous benefits, agrochemicals have been reported to be the main cause of various health and environmental problems. Each year, approximately 1 million deaths and cases of chronic diseases globally are attributed to pesticide poisoning (Mostafalou & Abdollahi, 2013), as they can enter the body through inhalation, ingestion, or dermal contact. People more at risk are workers in pesticide manufacturing factories, pesticide applicators, children, and elderly people. Studies have linked pesticides to chronic diseases, such as cancer (Cavalier et al., 2023; de Graaf et al., 2022), diabetes (Hutchinson et al., 2008; Tyagi et al., 2021), and respiratory, reproductive, and neurotoxic disorders (Mostafalou & Abdollahi, 2013). Agrochemicals also have several environmental consequences such as soil and water contamination, which lead to threats to aquatic life and terrestrial biodiversity, besides the risk of resistance development in pests and pathogens (Himani et al., 2022).

Therefore, although agrochemicals have been a key tool for increasing crop yields around the world for decades, they have become an ill-suited strategy for managing biological risks and improving agricultural production.

15.5.2 Biotechnologically modified plant-resistant varieties

Another strategy for improving agriculture is the use of improved crop varieties that confer plant resistance to both abiotic and biotic threats. Several disciplines work together to achieve these plant optimizations, such as agronomy, biotechnology, molecular biology, etc. (Varshney et al., 2011). As for biotechnology, it offers great potential and has a broad scope for crop improvement, protection, and management. It can be employed to provide new and better breeds; improve crop quality and resistance to stress; and enhance shelf life, among others. An important branch of this science is genetic engineering, which focuses on creating stress-resistant crop varieties, which involves isolating a specific gene, combining it with a desirable vector to form a recombinant DNA molecule, and then introducing that gene into the plant genome to confer a new function or capability (Parmar et al., 2017).

As mentioned before, the use of agrochemical pesticides for biotic stress control is considered hazardous to farmers and consumers and is environmentally unsustainable. In this sense, horticultural biotechnology has been leading the example of transgenic crops since the commercial approval of the first transgenic tomato, "Flavr-Savr," with enhanced shelf life in 1994 (Kramer & Redenbaugh, 1994). Since then, traits such as increased tolerance to biotic stresses (e.g., insect, pest, disease resistance) have been introduced to crops. Various genetic transformation systems, including electroporation, *Agrobacterium tumefaciens*-mediated transformation, and biobalistics, have been successfully developed in different crops since the early 1990s

(Budeguer et al., 2021; Kumar et al., 2020). Moreover, recent advancements in research and genome editing technology have made modifying crop genomes relatively easy, accurate, and precise (Kumar et al., 2020). Several approaches are employed to enhance plant varieties, such as targeted mutagenesis, precise modification of endogenous genes, and site-specific insertion of beneficial trait genes. To achieve this, there is a variety of gene editing tools like site-specific nucleases, zinc finger nucleases, Transcription Activator-Like Effector Nucleases, and clustered regularly interspaced short palindromic repeats/Cas9 system, to mention some (Kumar et al., 2020).

As an example, drought stress is a major threat to plant production around the world and, together with other climatic changes, causes a significant loss in crop yields. Thus, enhancing the performance of crop plants under drought stress is a significant breeding goal for scientists. Plant hormones participate during the response to drought stress, playing a vital role in plant tolerance through the regulation of various processes like stomatal closure, root growth, and the synthesis of protective metabolites (Anwar et al., 2018). In studies on transgenic groundnut plants for water stress resistance, the ABA independent transcription factor (DREB1A) transgenic plants showed a notably enhanced reaction to water scarcity, promoting significant root growth, particularly in the deeper soil layers (Gantait & Mondal, 2018). The introduction of transgenic DREB1A into groundnut (genetically modified with the rd29 promoter) consistently modified the root system across the soil profile, resulting in increased root length density to improve the water extraction efficacy (Bhatnagar-Mathur et al., 2007). Consequently, the transgenic groundnut exhibited improved pod yield, enhanced yield components, and an increased harvest index (Bhatnagar-Mathur et al., 2007; Gantait & Mondal, 2018).

Another important application of transgenic crops for mitigating plant stress is the development of resistance to insects. The toxicity of Cry proteins produced by *Bacillus thuringiensis* (Bt) is highly effective against insect larvae, with lethal effects on different insect species but not on humans or other mammals (Gonzalez-Vazquez et al., 2021). Bt-Cry genes have been successfully used to create transgenic crop varieties with insect resistance, starting with tomato plants resistant to *Manduca sexta* and *Heliothis virescens* (tobacco hornworm and budworm, respectively) (Fischhoff et al., 1987). Additionally, genes such as protease inhibitors, trypsin inhibitors, lectins, and others have been used to confer resistance to insect pests in various crops. For instance, in 2017, Schneider et al. developed a transgenic sugarcane variety overexpressing the sugarcane cysteine peptidase inhibitor 1 (*CaneCPI-1*) gene, providing resistance against *Sphenophorus levis*, a sugarcane weevil causing stem base destruction (Schneider et al., 2017).

Over the last decades, the worldwide acceptance of genetically modified crops has yielded economic and environmental advantages, including higher crop yields, decreased use of agrochemical pesticides, reduced carbon dioxide emissions, elevated farmer income, and enhanced consumer health (Kumar et al., 2020). For example, by the year 2015, the adoption of transgenic insect-resistant and herbicide-tolerant crops reduced pesticide spraying by 618.7 million kg and, as a result, decreased the environmental impact associated with pesticide use on these crops (Brookes & Barfoot, 2017). There are also numerous agronomic and economic benefits, for example, an increase of one-seventh of yield in food crops has been attributed to modified crops, which equals to converting more

than 300 million acres for conventional crops, along with the respective demand of fertilizer and irrigation (Zhang et al., 2016). Furthermore, by 2016, the global increase in farm income from modified food reached almost triple that of the previous 10 years (Brookes & Barfoot, 2018; Zhang et al., 2016).

Nevertheless, certain apprehensions and concerns have been expressed regarding the ecological risks and potential hazards for human consumption associated with genetically modified crops. Five main concerns have been manifested against transgenic crops and are listed below:

1. Biosafety issues related to transgenic crops in terms of potential threat to human health (toxicity and allergenicity) and the environment (the possibility of transgene flow into the environment and adverse effect on biodiversity). Nevertheless, with only a few exceptions, most of the studies related to the health hazards of transgenic crops have not reported adverse effects of a diet comprising transgenic food, on animal health (de Vos & Swanenburg, 2018; Kumar et al., 2020);
2. Resistance breakdown, as an extensive cultivation of transgenic crops may increase chances of resistance development in the targeted insect population and weeds, due to high selection pressure, but even though there are few examples of pest resistance to *Bt* modified crops (van Rensburg, 2007), experience has demonstrated that resistance in crops can remain effective against most pests even after a decade (Carrière et al., 2010);
3. Adverse effects on nontarget organisms, as it is possible that killing of the major pests may allow secondary pests to take over as major pest (Kumar et al., 2020);
4. Cost for commercialization, as the development and commercialization of transgenic crop products have a high cost, due to the lengthy safety assessments and the complex regulatory approval processes (Smart et al., 2017);
5. Oligopoly of multinational companies, as most of the commercialized transgenic crops are developed and patented by a few multinational companies (i.e., Monsanto, Syngenta, Bayer CropScience, Dupont) leaving farmers with fewer choices in the seed market (Kumar et al., 2020).

Despite the rejection of the population of modified crop varieties, it remains an important strategy for ensuring crop resilience to the current environmental challenges, and those upcoming due to climate change. Especially considering that traditional techniques based on agrochemical compounds are no longer as effective and all the risks they represent. Thus, it is important to keep divulging the research advances to the general community, as well as the mechanisms of action, to eliminate the numerous prejudices upon the use of biotechnological approaches. Another innovative biotechnological strategy, which is being largely researched nowadays, is the use of beneficial microorganisms to improve plant development, health, and resilience while regenerating soil ecosystems.

15.5.3 Plant growth-promoting microorganisms-based bioinoculants

Recently, the use of beneficial microorganisms as bioinoculants to mitigate the effects of abiotic and biotic stresses has increased. Bioinoculants are environmentally friendly and sustainable biological products that contain beneficial microorganisms or their active metabolites. When applied to seeds, plant surfaces, or soil, these

microorganisms can enhance plant growth by increasing nutrient supply or availability to the host plant and providing protection against biotic and/or abiotic stresses (Santoyo et al., 2021). The beneficial microorganisms used in bioinoculants can be categorized as either PGPMs or biological control agents and their respective mechanisms of action include nitrogen fixation, phosphate solubilization, phytostimulation, induction of plant resistance, and antagonism against phytopathogens, among other functions (Lugtenberg & Kamilova, 2009).

PGPMs have shown potential to help with a range of plant stresses in their environment. An example is the role of PGPMs in acidity and alkalinity stress management; for optimal plant growth, it is crucial to monitor the soil pH and amend the soil to achieve optimal pH levels, preferably close to neutrality (Msimbira & Smith, 2020). The rhizobacteria family Bacillaceae is among the best described in their capacity to tolerate alkalinity and has a wide range of host plants, which makes it a suitable candidate to mitigate alkalinity stress in plants (Torbaghan et al., 2017). Another example is PGPM as a mitigator of heat stress; for instance, *P. putida* produces a heat shock protein that plays a vital role in increasing plant thermal tolerance, improving survival and growth of wheat plants under heat stress, significantly increasing the root and shoot length, dry biomass, tiller, and grain formation (Ali et al., 2011).

The utilization of PGPMs has proven successful in mitigating biotic stresses in crops, through their mechanisms of biological control. The *Bacillus* genus, in particular, is extensively employed for the biocontrol of phytopathogens in various agroecosystems, given the diverse and versatile nature of their mechanisms (Shafi et al., 2017; Villarreal-Delgado et al., 2017).

The application of PGPM-based bioinoculants is a cheap, ecofriendly, low-input, and time-saving strategy, compared to the development of stress-tolerant crop varieties (Ahmad et al., 2022). Furthermore, using beneficial microorganisms can improve the use of nitrogen, which helps reduce the impact of nitrogenous fertilization on the emission of GHGs (Suman et al., no date). On the other hand, one of the main problems encountered during the usage of these PGPMs is the development of suitable formulations and delivery systems (Hubballi et al., 2023). Besides, since bioinoculants may contain live cells, their storage and transportation require extra care and precaution, due to shorter shelf life (Basu et al., no date). Besides, the response of crops toward the bioinoculant is slower compared to agrochemicals, since microbial inoculums may take time to build their concentration and colonize plants' roots (Parnell et al., 2016).

Incorporating the interactions between PGPMs and plants into crop production programs offers a promising and sustainable solution to enhance agricultural production and mitigate stresses. However, the successful application of bioinoculants in the field depends significantly on scientific research and agrobiotechnological innovations. Under the constant threat of climate change, it is now more important than ever to describe and understand plant–microbe interactions in terms of stress resistance. Therefore, investigating and understanding the complex interactions among beneficial microorganisms, plants, and their environment, along with bioprospecting to harness these interactions on a large scale, are essential factors

to consider for translating knowledge from laboratories to the commercial production of effective bioproducts in agriculture.

Additional crop management strategies based on sustainability include resource conservation technologies (minimum soil disturbance, crop rotation, soil cover), cropping-system technologies, and socio-economic or political interventions. Several agronomic practices have shown yield improvements, such as: adapting seeds sowing dates, drip irrigation, generation of stress-tolerant plant varieties, optimized nitrogen use, etc. (Malhi et al., 2021).

15.6 Conclusion and future perspectives

As climate change persists and the population keeps growing, agriculture is subjected to increasing stressors that threaten food security around the world. It is important to study the impact of climate change on the diverse stress factors and thus how they will greatly impact crop production yields. Furthermore, there exist diverse innovative strategies that contribute to mitigating crop abiotic and biotic stresses and allow an important decrease in the use of agrochemicals and the negative effects they provoke, such as the use of biotechnologically modified plant species. Another promising alternative is the use of microbial inoculants which act as biofertilizers and biofungicides. This strategy favors soil quality, resilience, and health, reducing its erosion and increasing its microbial diversity. However, its optimization requires further research on microbial mechanisms and their beneficial relationships with important crops.

To meet current and future demands of crops for feeding the global population and ensuring food security during climate change, it has become urgent to migrate to a more integral crop stress management approach, including innovative and sustainable mitigation strategies. It is also fundamental to educate farmers on the importance of ecological cropping systems and the long-term benefits they provide. Technology transfer to farmers has to be facilitated as it contributes to its validation and better acceptability based on the positive results obtained.

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Rising CO₂, thriving plants: unraveling growth mechanisms and adaptive strategies

16

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16.1 Introduction

The unprecedented rise in atmospheric carbon dioxide (CO₂) levels, driven by anthropogenic activities such as fossil fuel combustion and deforestation, has emerged as a defining challenge of the 21st century (Anwar et al., 2019). From the preindustrial levels of approximately 280 ppm, atmospheric CO₂ concentrations have surpassed 420 ppm, with projections suggesting further escalation by the end of this century (Farhat, 2023). A comprehensive review by Ainsworth et al. (2020) highlights the rapid escalation of anthropogenic CO₂ emissions, which surged at an annual rate of 1.1% throughout the 1990s, accelerating to 3.3% per year during the 2000s. Despite concerted global mitigation efforts, the relentless rise in CO₂ emissions persisted unabated, recording a global increase of 2% in 2017. Notably, a majority of these emissions were concentrated in China (3.5%) and India (2%) (Ainsworth et al., 2020). This surge holds profound implications for global ecosystems, particularly terrestrial plants, which act as primary mediators of carbon flux through photosynthesis. Understanding the ramifications of elevated CO₂ (eCO₂) on plant physiology, growth, and adaptation is imperative for predicting future agricultural productivity and ecosystem stability. eCO₂ influences multiple facets of plant biology, ranging from primary metabolism to secondary metabolite production. Enhanced carbon availability under elevated CO₂ conditions often leads to increased photosynthetic rates and biomass accumulation (Kirschbaum, 2011). However, the magnitude and sustainability of these responses vary across species, growth conditions, and environmental constraints. For instance, while C₃ plants, reliant on the Calvin cycle, exhibit pronounced stimulation in photosynthesis due to reduced photorespiration, C₄ plants display more subdued responses owing to their preexisting CO₂-concentrating mechanisms (Raines, 2011). Thus, unraveling the mechanistic underpinnings of these responses is critical for leveraging elevated CO₂ as a potential driver of agricultural resilience and sustainability.

The study of elevated CO₂ effects on plants is not merely of academic interest but also carries significant socio-economic and ecological relevance. With the global population projected to reach 10 billion by 2050, ensuring food security under changing climatic conditions is paramount. eCO₂ has the potential to enhance crop yields; however, it may also lead to trade-offs in nutritional quality and stress tolerance. Moreover, the interaction of elevated CO₂ with other environmental factors, such as ozone pollution, nutrient limitation, and water scarcity, adds layers of complexity to plant responses, necessitating comprehensive and integrative research.

This chapter aims to provide a holistic understanding of plant responses to elevated CO₂ by delving into mechanistic insights, morphophysiological adaptations, and interactions with environmental factors. The objectives of this chapter are threefold. First, it seeks to elucidate the biochemical and physiological mechanisms underpinning the plant growth and adaptation under elevated CO₂ conditions. This includes examining photosynthesis, hormonal regulation, source–sink dynamics, and secondary metabolism. Second, the chapter explores plant morphophysiological responses, encompassing changes in leaf morphology, root architecture, and biomass

accumulation. Third, it assesses the interplay between elevated CO₂ and environmental variables, such as nutrient availability, ozone stress, and water resources.

16.2 Mechanistic insights into elevated CO₂ and plant growth

16.2.1 *Photosynthesis and carbon assimilation*

Elevated atmospheric CO₂ profoundly influences photosynthetic processes and carbon assimilation, serving as a critical determinant of plant growth and productivity. Photosynthesis comprises two interconnected phases: light-dependent reactions that produce adenosine triphosphate (ATP) and nicotinamide adenosine dinucleotide phosphate and the Calvin cycle, where CO₂ is fixed into organic molecules. Elevated CO₂ augments the availability of substrate for RuBisCO, enhancing carboxylation while simultaneously suppressing oxygenation, thereby mitigating photorespiration, particularly in C₃ plants. Stomatal conductance (g_s), a pivotal factor in CO₂ flux regulation, exhibits a reduction under elevated CO₂ conditions. This response is mediated by complex interactions involving stomatal size, density, and the leaf-to-air vapor pressure deficit. Historical analyses indicate a significant reduction in stomatal density and pore size over the past century, a likely adaptive mechanism to maximize reductions in g_s in response to rising atmospheric CO₂ concentrations (Lawson & Blatt, 2014). This is consistent with the reports of lower g_s , reduced leaf transpiration, and enhanced water-use efficiency (WUE) under elevated CO₂ conditions (Katul et al., 2010; Leakey et al., 2009; Zhang et al., 2012). CO₂ enrichment bolsters photosynthesis by enhancing the chlorophyll content, RuBisCO activity, and carbon fixation, particularly in C₃ species, where the suppression of photorespiration leads to an increased photosynthetic efficiency. Doubling atmospheric CO₂ is projected to eliminate C₃ photorespiration entirely, significantly amplifying carbon assimilation (Bowes, 1991; Sage & Kubien, 2007). This phenomenon, often termed the “CO₂ fertilization effect,” facilitates greater production of photosynthates, which may fuel growth, repair oxidative damage, and enhance tolerance to environmental stressors such as ozone exposure (Fig. 16.1).

In *Arabidopsis*, elevated CO₂ accelerates starch and sugar accumulation and boosts the intermediates of respiratory glycolysis such as hexose-P and phosphoglycerate, enhancing the respiration potential (Watanabe et al., 2014). However, a general reduction in dark respiration has also been observed under CO₂ enrichment. Elevated CO₂-induced declines in g_s reduce transpiration and canopy water use, improving soil moisture retention and potentially enhancing yields under water-limited conditions (Ainsworth et al., 2002; Sreeharsha et al., 2015). Enhanced WUE has been reported in C₃ crops like chickpea and potato under simultaneous ozone and CO₂ enrichment, reflecting the mitigatory effects of CO₂ on oxidative stress (Kumari & Agrawal, 2014; Singh et al., 2017). The role of mesophyll cells and guard cells in CO₂ sensing is paramount. Carbonic anhydrase activity in guard cells and sugar-responsive

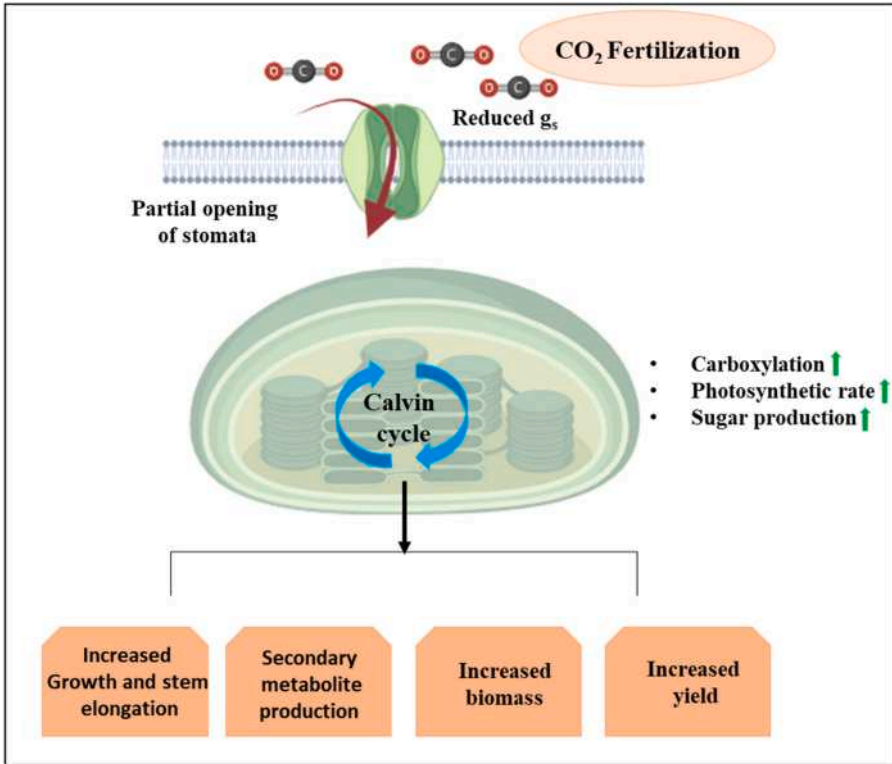


Figure 16.1 Mechanistic pathways of CO₂ fertilization: enhanced photosynthesis, carbon assimilation, and biomass allocation under elevated CO₂ conditions.

mechanisms involving hexokinase are critical for CO₂-mediated stomatal movement (Hu et al., 2010; Xu et al., 2016). Additionally, elevated CO₂ regulates stomatal development by altering internal leaf CO₂ concentrations (C_i), with evidence suggesting long-term enrichment reduces stomatal density and pore size, thereby modulating g_s and water loss (Medlyn et al., 2005). These changes represent an essential adaptation to rising CO₂ levels, enabling plants to balance carbon assimilation with water conservation.

Photochemical efficiency under elevated CO₂ often increases, potentially offsetting oxidative damage caused by stressors like ozone. Enhanced chlorophyll content under elevated CO₂ has been documented across multiple studies, with a corresponding rise in the photosynthetic efficiency (evidenced by higher Fv/Fm ratios) observed in species such as wheat, chickpea, and potato (Agrawal & Deepak, 2003; Kumari & Agrawal, 2014; Mishra et al., 2013). The adaptive increase in chlorophyll facilitates higher light absorption and energy conversion, bolstering initial photochemistry and sustaining carbon fixation under enriched CO₂ conditions. While CO₂ enrichment enhances the photosynthetic performance, it may also lead to photosynthetic

acclimation. Prolonged exposure to elevated CO₂ can result in excessive carbohydrate accumulation, suppressing genes encoding photosynthetic proteins and reducing RuBisCO content. This acclimation effect, characterized by feedback inhibition and a decline in photosynthetic capacity, highlights the limitations of sustained carbon assimilation under elevated CO₂. In some cases, excessive sugar accumulation can cause chloroplast-level damage or the uncoupling of photosynthesis from g_s , further constraining photosynthetic efficiency (Rodrigues, 2017). Overall, the mechanistic insights into elevated CO₂ effects on photosynthesis and carbon assimilation underscore its dual role as a growth stimulator and regulator. While the “CO₂ fertilization effect” offers substantial gains for C₃ plants, long-term acclimatory responses necessitate further exploration to optimize the benefits of elevated CO₂ in the context of changing climatic and environmental stressors.

16.2.2 Role in stress signaling and growth modulation

Elevated CO₂ plays a pivotal role in fine-tuning stress signaling pathways, particularly through its influence on abscisic acid (ABA) biosynthesis and downstream signaling cascades. As a key phytohormone, ABA mediates the plant's response to environmental stressors, such as drought, salinity, and oxidative stress. Under elevated CO₂ conditions, plants exhibit a recalibration of ABA dynamics, characterized by moderated ABA accumulation and enhanced signaling efficiency (Liang et al., 2024). This regulation mitigates the intensity of stress-induced physiological disruptions, fostering a more balanced and adaptable state.

Elevated CO₂ also enhances the activity and expression of critical antioxidant enzymes, including superoxide dismutase, catalase, and ascorbate peroxidase (Wang et al., 2021). These enzymes constitute the primary defense system against reactive oxygen species (ROS), which are often overproduced during stress conditions. By accelerating the detoxification of ROS, elevated CO₂ minimizes cellular oxidative damage, preserving the membrane integrity, protein functionality, and photosynthetic efficiency. This dual modulation—attenuating stress signaling via ABA while bolstering ROS-scavenging mechanisms—enables plants to achieve a harmonious interplay between the growth and defense (Roy & Mathur, 2021). The result is an optimized allocation of resources, where energy-intensive stress responses are dialed down, and metabolic reserves are redirected toward sustaining growth processes, even under suboptimal environmental conditions. Additionally, elevated CO₂-induced modulation of stress signaling integrates with other hormonal pathways, such as auxins, cytokinins, and gibberellins, to maintain developmental plasticity. This integrative approach ensures that stress mitigation mechanisms do not hinder growth, allowing plants to thrive in challenging environments while maintaining resilience against oxidative and abiotic stressors.

16.2.3 Secondary metabolism

eCO₂ exerts a significant influence on plant secondary metabolism, particularly on the phenylpropanoid pathway, leading to altered production of phenolic compounds,

flavonoids, and other metabolites. These shifts have important implications for plant growth, defense mechanisms, and nutritional quality.

16.2.3.1 Phenolic compounds and flavonoids

The existing literature predominantly indicates that flavonoids exhibit an increasing trend under eCO₂. Studies consistently report elevated levels of total flavonoids and tannins in plants exposed to higher CO₂ concentrations (Becker & Kläring, 2016). For instance, eCO₂ enhanced flavonoid accumulation in most cases (Bindi et al., 2001; Mishra et al., 2024b), while lignin levels generally remained unaffected (Stiling & Cornelissen, 2007). However, this response is not universal. A study on 12 rice cultivars observed a decrease in both total and individual phenolic compounds, alongside a reduction in the overall antioxidant capacity of the plants (Goufo et al., 2014). These contrasting findings suggest a nuanced response, potentially influenced by species, tissue type, and environmental conditions. For example, flavonoid accumulation appears more pronounced in leaves, while reductions in fruit may contribute to diminished nutritional value under eCO₂ conditions.

16.2.3.2 Mechanisms underlying phenolic accumulation

The increase in phenolics under eCO₂ is hypothesized to result from enhanced enzymatic activity within the phenylpropanoid pathway. Key enzymes, such as phenylalanine ammonia lyase, which catalyzes the first committed step in this pathway, are often upregulated under elevated CO₂ (de Rezende et al., 2015; Matros et al., 2006). This transcriptional activation may drive higher phenolic production. Additionally, eCO₂ might activate specific transferases or hydroxylases, further boosting the biosynthesis of phenolic compounds. Another proposed mechanism involves the shikimate pathway, which serves as a precursor to phenolic biosynthesis. Under eCO₂, increased photosynthetic activity leads to higher sugar levels, which may be funneled into the shikimate pathway, providing an excess of precursors for phenolic and flavonoid synthesis. This process likely reflects a metabolic adaptation to utilize surplus photosynthates, with secondary metabolites acting as carbon sinks.

16.2.3.3 Terpenes and other carbon-based secondary metabolites

Compared to phenolics, the response of terpenes to eCO₂ is less pronounced. While some herbaceous species, such as lima bean and cotton, showed increased terpene concentrations under eCO₂ (Ballhorn et al., 2011; Gao et al., 2008; Wu et al., 2011), woody species like oak exhibited inhibited terpene production (Loreto et al., 2001). This suggests species-specific and structural differences in metabolic responses to elevated CO₂. Carotenoids and sesquiterpenes were largely unaffected by eCO₂ in crops like tomato and tobacco (Krumbein et al., 2012; Matros et al., 2006).

16.2.3.4 N-containing secondary metabolites

eCO₂ also influences nitrogen-containing secondary metabolites, though the response is complex and varies by compound and species. A general hypothesis suggests that

N-based secondary metabolites might decrease under eCO₂ due to a dilution effect caused by the reduced leaf nitrogen content (Gleadow et al., 2009; Lindroth et al., 2000). However, empirical studies challenge this notion. Cyanogenic glycosides, for example, increased in the leaves of cassava and red lettuce under eCO₂ (Becker & Kläring, 2016; Gleadow et al., 2009). Similarly, alkaloid production, including compounds such as nicotine, morphine, and scopolamine, was significantly enhanced (Jia et al., 2014). This response might result from a metabolic trade-off, where the decreased production of nitrogen-demanding primary metabolites reallocates nitrogen to secondary metabolism, particularly in alkaloid biosynthesis (Matros et al., 2006).

16.2.4 Implications for the phenylpropanoid pathway

The phenylpropanoid pathway exemplifies how eCO₂ drives metabolic shifts to optimize resource utilization and enhance adaptive traits. By increasing the production of flavonoids, phenolics, and related compounds, plants bolster their antioxidative capacity and stress tolerance. However, these changes are not without trade-offs. The observed decreases in the antioxidant capacity in certain species, such as rice, highlight potential vulnerabilities, particularly in crops critical for human nutrition. Furthermore, the interplay between carbon and nitrogen metabolism under eCO₂ shapes the overall phenylpropanoid pathway response. Increased carbon availability promotes phenolic accumulation, while altered nitrogen allocation affects the synthesis of N-containing metabolites, balancing growth, defense, and metabolic storage functions.

16.2.4.1 Source–sink relationships under elevated CO₂

Impact on carbohydrate allocation and storage

eCO₂ enhances photosynthetic carbon assimilation, leading to an increase in the production of carbohydrates. These additional photo-assimilates are transported from source tissues (leaves) to sink tissues (roots, fruits, seeds, and developing organs), affecting their growth and storage dynamics. The increased carbohydrate availability boosts energy reserves in sink tissues, often improving storage capacities for starch, sugars, and other metabolites. However, the magnitude of carbohydrate allocation is influenced by the sink strength, the capacity of sink tissues to utilize and store these assimilates (Fernie et al., 2020). Enhanced carbohydrate allocation to sink tissues under eCO₂ supports root proliferation, seed filling, and fruit development. This reallocation may also lead to changes in metabolic activity within the sinks, including enhanced enzyme activity for starch biosynthesis and storage protein accumulation. However, sinks with lower activity or limited storage capacity may become saturated, potentially causing feedback inhibition on photosynthesis.

16.2.4.2 Growth trade-offs between vegetative and reproductive organs

Initially, the increased carbon supply under eCO₂ often promotes vegetative growth, with an emphasis on leaf expansion, stem elongation, and root development

(Gray & Brady, 2016; Madhu & Hatfield, 2013; Mishra et al., 2024c; Pritchard et al., 1999). However, as the sink strength of reproductive organs (e.g., flowers, fruits, seeds) increases during developmental transitions, the allocation of carbohydrates shifts. This trade-off supports reproductive development at the expense of continued vegetative growth (Fig. 16.2).

The timing and extent of this transition depend on the species, developmental stage, and environmental conditions. Crops with strong sink capacities, such as cereals and legumes, exhibit significant improvements in yield-related traits, including the seed size and starch content. Conversely, plants with weaker reproductive sinks may experience limited benefits, as vegetative growth dominates resource allocation, potentially reducing reproductive output. This dynamic trade-off

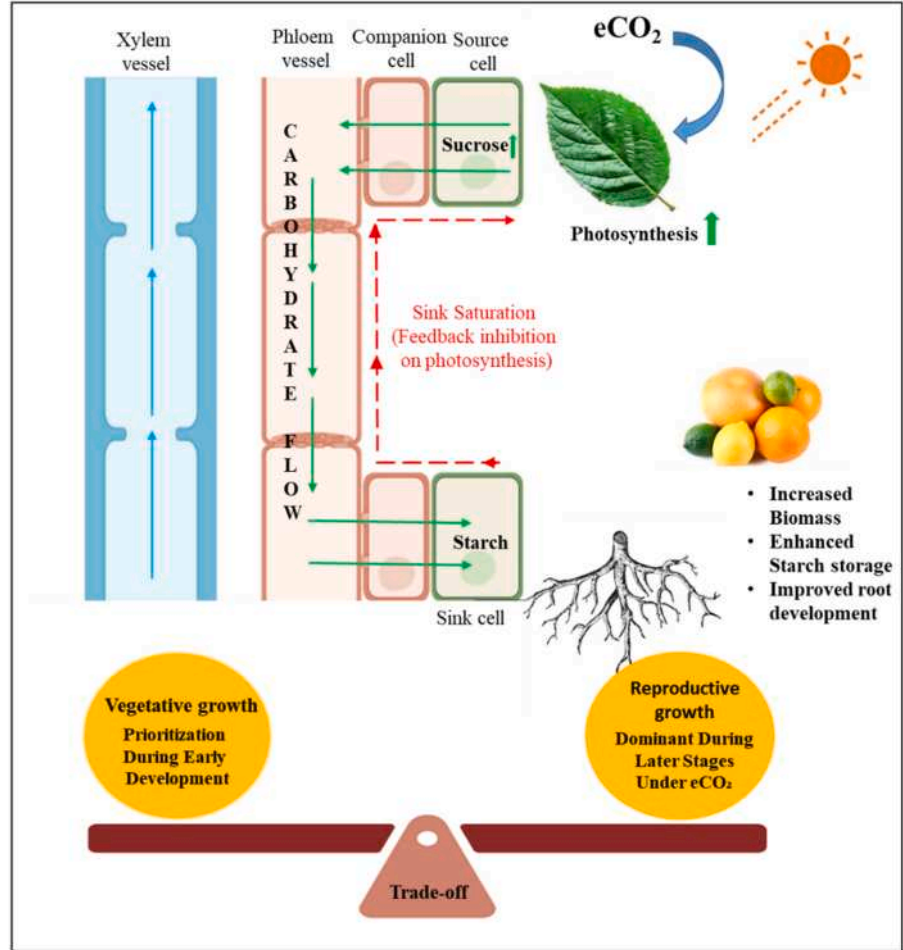


Figure 16.2 Source–sink dynamics and carbohydrate allocation under elevated CO₂.

reflects an adaptive strategy to optimize resource use, balancing growth demands with reproductive success under elevated CO₂.

16.3 Plant morphophysiological responses

eCO₂ levels significantly influence plant morphophysiological traits, enhancing the photosynthetic efficiency and biomass accumulation through increased carbon assimilation (Fig. 16.3). Morphologically, plants exhibit augmented leaf area, thicker leaves, and altered stomatal density, optimizing the WUE. Physiologically, eCO₂ modulates the nutrient uptake, alters hormone signaling, and enhances carbon–nitrogen interactions, often leading to changes in resource allocation.

16.3.1 Leaf morphology and canopy structure

Under eCO₂ conditions, plants typically exhibit an increased rate of leaf initiation, accelerated elongation, and enhanced leaf area (Gamage et al., 2018). This leads to an expansion of canopy size, characterized by a greater number of leaves and larger individual leaf areas, thereby increasing the photosynthetic surface area per plant. However, the response of leaf area to CO₂ enrichment is not universally consistent (Srinivasan et al., 2017). For instance, in rice, while the leaf area increases during the

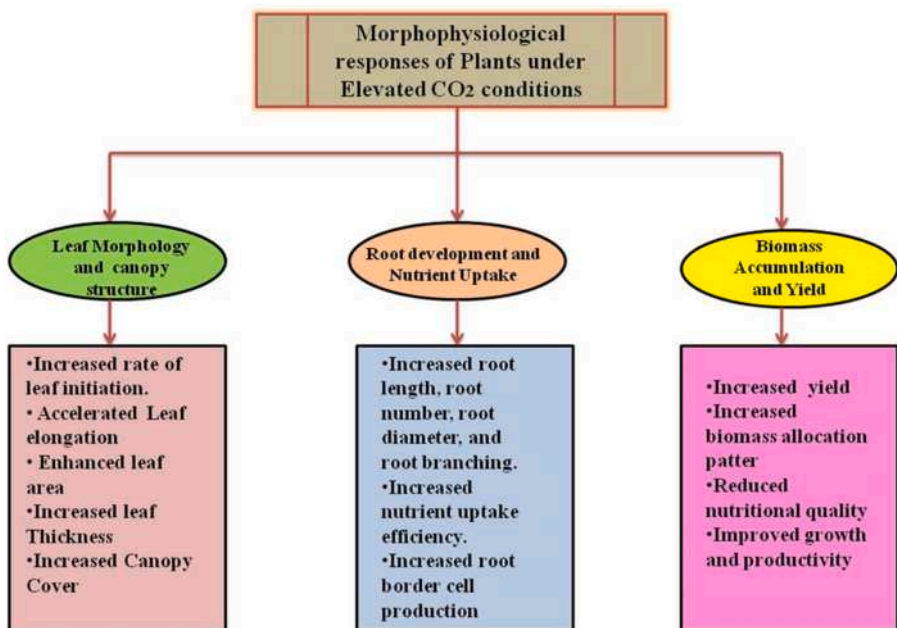


Figure 16.3 Figure illustrating morphophysiological responses of plants under elevated CO₂ conditions.

seedling and early vegetative stages under eCO₂, it often declines during the later vegetative and reproductive stages (Gamage et al., 2018; Makino, 2011).

In addition to the leaf area, eCO₂ significantly alters the leaf thickness and internal anatomy. For example, soybean (*Glycine max*) leaves exhibited the development of an extra layer of palisade cells under elevated CO₂ (Madhu & Hatfield, 2015), while in *Pinus radiata* leaves, elevated CO₂ enhanced both the mesophyll cross-sectional area and vascular tissue area (Araújo et al., 2011). These anatomical modifications are critical for improving the photosynthetic capacity and the efficiency of assimilate transport within the plant (Ren et al., 2019).

Moreover, plants grown under eCO₂ exhibit significant variability in leaf mass per unit area (LMA), a trait that can partly explain intraspecific differences in growth responses to eCO₂ (Oguchi et al., 2016). In wheat (*Triticum aestivum* L.), higher LMA correlates with increased photosynthetic rates per unit leaf area, greater leaf nitrogen content on an area basis, enhanced growth rates, and improved yield under eCO₂ conditions (Thilakarathne et al., 2012). Variations in LMA also reflect the plant's ability to allocate resources in response to environmental stimuli (Poorter et al., 2019).

It is hypothesized that the changes in leaf anatomy and morphology under eCO₂ contribute to an increased supply of photoassimilates to the apical meristem, thereby promoting the development of leaf primordial (Mishra et al., 2025; Sharma et al., 2014). Additionally, the elevated availability of soluble carbohydrates from expanding leaf blades is believed to play a key role in driving higher rates of leaf elongation, leaf area expansion, and the overall plant growth observed under eCO₂ (Gamage et al., 2018).

Elevated CO₂ significantly impacts the photosynthetic pigments of plants, particularly chlorophyll, which plays a central role in light absorption and photosynthesis. This response is attributed to the greater availability of carbon, which drives photosynthesis and supports the synthesis of pigments like chlorophyll (Hussain et al., 2021). Additionally, an increase in photosynthetic pigments under eCO₂ reflects an adaptive mechanism to optimize carbon fixation and growth. However, the magnitude of this effect is influenced by nutrient availability, particularly nitrogen, which is essential for chlorophyll biosynthesis. Under nitrogen-limited conditions, the positive effects of eCO₂ on pigment levels may be constrained due to restricted nitrogen uptake and allocation (Murchie et al., 2022).

16.3.2 Root development and nutrient uptake

Under eCO₂ conditions, the allocation of photosynthetically derived carbon to roots increases, resulting in a more pronounced stimulation of root growth compared to other plant organs. Enhanced root growth under eCO₂ is characterized by increments in the root length, root number, root diameter, and root branching (Calleja-Cabrera et al., 2020; Madhu & Hatfield, 2013). For instance, it was reported that rice plants grown in Stagnic Anthrosol soil under 550 $\mu\text{L L}^{-1}$ CO₂ exhibited a 45% increase in root biomass, a 44% increase in root volume, a 31% rise in the number of adventitious roots, and a 37% extension in overall root length compared to those

grown under ambient CO₂ conditions (350 $\mu\text{L L}^{-1}$) (Jin et al., 2015). Similar enhancements were observed in white lupin (*Lupinus albus*), which displayed a greater number of root clusters and a higher proportion of lateral roots under eCO₂ conditions (O'Sullivan et al., 2020). Consistent trends have been documented in other crops such as chickpea, soybean, field pea, wheat, sorghum, and cotton (Butterly et al., 2015; Chakrabarti et al., 2020; Madhu & Hatfield, 2013; Mishra et al., 2024). Structural modifications such as increased stele and cortex diameter, root diameter in the root hair zone, and greater carbohydrate storage capacity are also prevalent under CO₂ enrichment. These changes improve the root quality and functional efficiency (Nirmalaruban et al., 2024). Enhanced root growth benefits mycorrhizal fungi and glomalin production, contributing to improved soil aggregation and ecosystem processes (Mishra et al., 2024).

However, CO₂-induced root proliferation may alter resource allocation, with studies showing less efficient nutrient and water uptake per unit root length despite greater total root length density. Shifts in rooting patterns, including deeper rooting distributions and increased lateral branching, influence soil nutrient dynamics, potentially enhancing the overall nutrient uptake but reducing tissue nutrient concentration (Duque & Villordon, 2019). eCO₂ also increases root border cell production, as observed in pea seedlings, where cell numbers increased by over 50% and 100% under 3000 and 6000 $\mu\text{mol mol}^{-1}$ CO₂, respectively (Madhu & Hatfield, 2013; Zhao et al., 2000). These changes enhance root exudates into the rhizosphere, stimulating microbial and fungal activity and creating a more favorable soil environment for plant growth (Ma et al., 2022).

These morphological alterations in roots facilitate an expanded distribution within the root zone, thereby enhancing the nutrient uptake efficiency (Yetgin, 2024). A comparable finding was reported by Jin et al. (2012), who demonstrated a significant positive correlation between root length and phosphorus (P) uptake under both ambient and eCO₂ conditions. It was reported that the increased root length observed under eCO₂ contributed to enhanced phosphorus acquisition. These results suggest that root growth responds positively to eCO₂, allowing roots to explore a greater soil volume. This expansion of the root system consequently improves the plant's nutrient uptake capacity (Ma et al., 2020).

16.3.3 Biomass accumulation and yield

Elevated atmospheric CO₂ acts as a carbon fertilizer, boosting the plant growth and crop productivity by enhancing the photosynthetic rates. This increase in photosynthetic rates leads to a greater accumulation of photoassimilates, which supports improved growth and increased yields (Bhargava & Mitra, 2021). ATP generated through respiration drives essential physiological processes, contributing to growth, yield, and nutritional quality. However, under elevated CO₂ conditions, a larger share of ATP is allocated to growth and yield-related activities, often reducing the resources available for processes that enhance nutritional value. This shift highlights potential trade-offs between increased productivity and the nutrient quality of crops (Burgess et al., 2023). eCO₂ has

been associated with increased economic yield in crops through various factors, such as larger seed or grain size, a higher number of seeds or grains per pod, plant, ear, or panicle, and/or the development of additional reproductive structures per plant (Maity et al., 2023). In C_3 crops like wheat, rice, soybean, and mung bean, the yield enhancement under elevated CO_2 is primarily attributed to increased aboveground biomass production, which supports a greater number of reproductive structures (Cai et al., 2016; Jin et al., 2017).

Additionally, free-air CO_2 enrichment (FACE) experiments examining the response of other C_3 crops, including sugar beet (*Beta vulgaris*), potato (*Solanum tuberosum*), barley (*Hordeum vulgare*), and oilseed rape (*Brassica napus*), have demonstrated yield improvements under CO_2 enrichment (Hatfield et al., 2020). For instance, potato yield increased significantly due to enhanced tuber production, although aboveground dry matter production remained unchanged (Doddrell et al., 2023). Moreover, Dubey et al. (2015) analyzed data from 19 studies conducted across nine countries and concluded that wheat exhibited positive responses in growth and yield components under varying levels of eCO_2 .

Elevated CO_2 not only impacts the crop growth and yield but also significantly affects the crop quality, which encompasses a range of factors including assimilate partitioning, storage, nutritional composition, and post-harvest characteristics (Kumar et al., 2023). The elemental (e.g., zinc, iodine) and macromolecular (e.g., protein) composition of plant tissues are expected to alter in a high- CO_2 environment (Kant et al., 2012). Among the various aspects of yield quality, protein and nitrogen content have been extensively studied under CO_2 enrichment (Uddling et al., 2018).

A decline in grain protein content is commonly observed, largely attributed to nitrogen dilution caused by increased photosynthesis and carbohydrate accumulation under eCO_2 (Panozzo et al., 2014). In cereals like wheat, rice, and barley, reductions of up to 15% in grain protein levels have been documented, alongside an overall decline in amino acid concentrations. Such declines in cereal grain quality could have significant health and economic implications (Shaheen et al., 2022).

Moreover, elevated CO_2 alters the concentrations of macro- and micronutrients in crops, though the effects are less pronounced compared to nitrogen. Potassium and phosphorus levels may vary depending on growth conditions, while elements like sodium, calcium, magnesium, sulfur, iron, zinc, manganese, and aluminum have been reported to decrease significantly in wheat grain under elevated CO_2 compared to ambient conditions (Ebi et al., 2021). A meta-analysis by (Loladze, 2014) further underscores the reduction in several essential elements, including macroelements like sulfur, in crops grown under eCO_2 , highlighting its potential implications for food security and nutritional quality.

16.4 Interaction with environmental factors

16.4.1 Nutrient limitations

It is one of the controversial topic in global biogeochemistry. There are various parameters like nitrogen (N) availability affects terrestrial carbon (C) sequestration,

because of this disagreement, it is very difficult to predict future worldwide terrestrial C sequestration. Significant alterations in plant physiology and ecosystem dynamics are caused by the rising atmospheric CO₂ levels, mostly due to the “CO₂ fertilization effect.” Increased biomass production and plant growth result from this impact, which intensifies photosynthesis. However, the long-term sustainability of this growth is constrained by the interplay with nutrient restrictions, particularly those related to N and P (Krämer et al., 2022; Zhang et al., 2024). Increased CO₂ causes plants to produce more carbohydrates, which raises their food requirements. However, because of plant physiological limitations or restrictions in soil availability, nitrogen uptake frequently does not scale proportionately. “Dilution effect” is the term used to describe how this imbalance lowers the concentrations of nutrients in plant tissues (Liu et al., 2022). These interactions are made worse by environmental stressors like drought and global warming. For instance, increased CO₂ frequently increases the water efficiency by decreasing the transpiration and stomatal conductance, but this does not result with improved nutrient uptake, especially when there is water or nutrient stress (Liu et al., 2022). With increasing temperature, the breakdown of soil organic matter without necessarily increasing nutrient availability, and drought conditions restrict nutrient mobility in the soil, these combined stressors can intensify nutrient constraints (Lee et al., 2023; Zhang et al., 2024). To address this issue, a complete approach that incorporates improved soil nutrient management, crop breeding for higher nutrient-use efficiency, and sustainable agriculture practices tailored to various climatic conditions is required. Long-term studies using state-of-the-art methods, like FACE systems, are necessary to comprehend how elevated CO₂ interacts with nutrient cycling in practical settings and to develop strategies to maintain agricultural productivity and ecosystem resilience (Cao et al., 2022; Krämer et al., 2022).

16.4.2 Ozone (O₃) and other stresses

Plant physiology and productivity are intricately influenced by the interplay between the rising atmospheric CO₂ levels and other environmental stressors, such as O₃. Understanding how these climate-driven factors interact is critical for predicting their impact on natural ecosystems and agricultural systems. Such insights are essential for devising robust crop improvement strategies and breeding programs tailored to the challenges posed by climate change. One of the well-recognized phenomena linked to elevated CO₂ is the “CO₂ fertilization effect,” which primarily benefits C₃ plants. These species, including key crops like rice and wheat, experience enhanced photosynthesis and reduced photorespiration under high CO₂ conditions, leading to significant increases in biomass. Studies suggest that C₃ crops can produce 15%–41% more yield under elevated CO₂, demonstrating the potential for substantial productivity gains (Ainsworth & Long, 2021). However, the advantages of increased CO₂ do not occur in isolation but are modulated by interactions with other environmental stressors. For instance, while elevated CO₂ promotes the plant growth, it can simultaneously exacerbate certain biotic stressors. Enhanced CO₂ levels have been shown to boost the growth of pathogenic fungi like *Sphaerotheca fuliginea*,

intensifying disease symptoms in crops such as cucurbits (Singh et al., 2023). This suggests a complex synergistic interaction where elevated CO₂ not only fosters the plant growth but also enhances pathogen virulence, posing a dual-edged challenge for crop management. O₃, a major air pollutant, represents another critical abiotic stressor that adversely affects plant health. Elevated O₃ accelerates leaf senescence, reduces biomass, and inhibits photosynthesis through mechanisms such as reduced carboxylation efficiency and damage to the photosynthetic electron transport chain (Ainsworth et al., 2012; Paoletti & Grulke, 2005; Xu et al., 2022). Prolonged exposure to high O₃ concentrations has been linked to significant growth retardation in key crops like soybean and wheat. Interestingly, the interaction between elevated CO₂ and O₃ introduces additional layers of complexity. While increased CO₂ can mitigate some of O₃'s detrimental effects by enhancing the photosynthetic capacity, it cannot fully counteract O₃-induced damage (Mishra et al., 2024b; Mishra et al., 2024c). For example, eCO₂ may reduce stomatal conductance, limiting O₃ uptake in some scenarios, but higher temperatures associated with climate change can reverse this benefit by increasing stomatal opening and thereby O₃ absorption (Hansen et al., 2019).

Beyond abiotic stresses, plants also face biotic challenges from pathogens and herbivores, with elevated CO₂ exerting varied effects on these interactions. Rapid plant growth under high CO₂ creates more biomass for pathogens to exploit, increasing vulnerability to fungal infections (Grover et al., 2015; Lahlali et al., 2024). Conversely, some studies suggest that elevated CO₂ can bolster plant immunity against specific diseases either by upregulating immune-related genes or by modulating defense hormone signaling (Roussin-Léveillé et al., 2024; Williams et al., 2018). The net impact of CO₂ on plant defense mechanisms is context-dependent, influenced by factors such as the plant species, the type of pathogen, and the environmental conditions. This dual potential for increased susceptibility or enhanced resistance underscores the importance of understanding how plants respond to simultaneous biotic and abiotic stresses.

In summary, the effects of elevated CO₂ on plants are multifaceted, ranging from improved growth and productivity to heightened susceptibility to certain stressors. When combined with environmental challenges like O₃ pollution, these interactions become even more intricate, requiring a nuanced approach to crop management (Mishra et al., 2024a). A comprehensive understanding of these dynamics will be pivotal in developing resilient agricultural systems capable of sustaining food security in a changing climate.

16.5 Advances in experimental approaches

Over the years, various techniques have been employed to study tree responses to elevated atmospheric CO₂ at different levels, including individual plant organs, entire trees, and ecosystems. Early investigations into the effects of elevated CO₂ were typically conducted in controlled environments, such as closed chambers or greenhouses. These approaches included: (a) branch and leaf chambers (Teskey, 1997); (b) phytotrons (Liu et al., 2004); (c)

controlled environment chambers (Kellomäki et al., 2000); and their variations. However, a major limitation of these methods is their tendency to create artificial conditions that do not accurately reflect natural ecosystems.

Efforts to develop experimental setups more representative of natural environments have led to the adoption of advanced techniques that allow varying degrees of interaction with the surrounding environment. These include: (d) open-top chambers (OTCs) (Vanaja et al., 2006); (e) FACE (Karnosky et al., 2001); and (f) screen-aided CO₂ control (Leadley et al., 1997).

Among these, OTC and FACE systems are now the most widely used methods for studying plant responses to elevated CO₂ under conditions that closely approximate natural ecosystems. These approaches have significantly improved the ecological relevance of experimental studies, providing more reliable insights into plant and ecosystem responses to increasing atmospheric CO₂ (Uprety et al., 2021).

16.5.1 Open-top chambers

OTCs are metal structures with transparent vertical walls made of materials like polyvinyl chloride or Plexiglas, designed with a frustum-shaped top. An opening at the center of the frustum facilitates air exchange, helping to minimize temperature and humidity variations within the chamber. CO₂-enriched air is delivered through a circular tube, with air blowers ensuring uniform distribution throughout the chamber (Uprety et al., 2021). The CO₂ concentration inside the OTC is continuously monitored using a CO₂ analyzer and regulated through computer-controlled inlet valves to maintain precise enrichment levels (Vanaja et al., 2006).

OTC is a widely adopted technique for studying the effects of elevated CO₂ on crops and ecosystems. It allows for dynamic tracking of temperature, light, and rainfall changes similar to those in open environments, without the costly and complex controls required for closed chambers (Macháčová, 2010). OTCs expose entire plants to treatments without restricting the root growth, providing a realistic simulation of field conditions. A key advantage of OTCs is their ability to control atmospheric variables while maintaining nearly identical soil conditions to those found in natural settings (Wang et al., 2021).

However, research is needed to enhance the efficacy of OTCs as a field experimental tool. Investigating fluid dynamics and heat exchange properties, particularly the effects of turbulence and altered wind flow paths within the canopy, is critical to understanding how elevated CO₂ influences plant growth. Such improvements will refine the reliability and applicability of OTCs in studying the climate change impacts on agriculture and ecosystems (Macháčová, 2010).

16.5.2 Free-air CO₂ enrichment system

FACE systems utilize a ring-shaped network of pipes encircling the experimental plot to deliver CO₂ through vertically oriented pipes. The CO₂ dosage is dynamically regulated based on the measured concentration within the plot and climatic conditions, such as wind speed and direction. To maintain consistent enrichment, the valves on the vertical pipes adjust to wind direction, opening and closing as necessary. This targeted release strategy

also optimizes efficiency by releasing CO₂-enriched air primarily in upwind directions, thereby minimizing experimental costs while ensuring uniform exposure across the plot (von Felten et al., 2007). In FACE plots, the natural environment is essentially unperturbed, as there are no barriers to light, precipitation, wind or pests. A major limitation to widespread use of FACE experimentation is the financial investment in the infrastructure, land and personnel needed to successfully run the experiments. As a result, the number of FACE experiments conducted is significantly lower compared to studies in controlled environments (Ainsworth & McGrath, 2010). Nonetheless, since plants in FACE setups grow in natural soil with minimal disruption to the surrounding microenvironment, these experiments provide some of the most accurate predictions of crop yield responses to elevated CO₂ levels.

16.5.3 Omics technologies

Advances in omics technologies, including transcriptomics, proteomics, and metabolomics, have significantly enhanced our understanding of plant responses to elevated CO₂ levels. These approaches provide a comprehensive perspective on the molecular, biochemical, and physiological adaptations plants undergo in high-CO₂ environment (Misra & Chen, 2015). Transcriptomic studies analyze gene expression patterns to identify the regulatory networks activated or suppressed under elevated CO₂. These investigations have revealed the upregulation of genes associated with photosynthesis, carbon metabolism, and nitrogen assimilation (Palit et al., 2020). For instance, genes encoding Rubisco, chlorophyll biosynthesis, and sucrose metabolism are often induced, reflecting plants' efforts to maximize carbon fixation and allocation. Additionally, genes involved in stress response pathways, such as antioxidant defense, may also be activated to mitigate oxidative damage associated with altered redox states under elevated CO₂ (Xu et al., 2015). Proteomic analyses focus on the abundance and modifications of proteins, offering insights into the functional machinery underlying plant responses. Elevated CO₂ can lead to an increased accumulation of photosynthetic proteins like Rubisco and those involved in carbohydrate metabolism (Kumar et al., 2020). Conversely, a decrease in proteins associated with nitrogen assimilation and defense responses has been observed, indicating resource reallocation. Proteomic studies also highlight post-translational modifications that regulate protein activity in response to changing CO₂ concentrations (Friso & van Wijk, 2015). Metabolomics provides a snapshot of the biochemical changes by profiling metabolites. Elevated CO₂ typically increases the levels of primary metabolites such as sugars and starch, reflecting enhanced carbon assimilation (Jorge & António, 2018). Secondary metabolites, including flavonoids, phenolics, and alkaloids, may also accumulate, contributing to improved stress tolerance and defense. These metabolic shifts demonstrate how plants reallocate resources to balance growth and defense under elevated CO₂ conditions (Qaderi et al., 2023). Integrating transcriptomic, proteomic, and metabolomic data enables a systems-level understanding of plant responses. Such studies have revealed coordinated changes in carbon and nitrogen metabolism, stress responses, and resource allocation. For example, elevated CO₂ often induces a carbon-nitrogen imbalance, where increased carbon availability is not matched by nitrogen uptake, leading to changes in metabolic fluxes and growth dynamics (Gao & Zhao, 2024).

16.5.4 Modeling plant responses

Crop simulation models serve as powerful tools for predicting potential outcomes in scenarios that are challenging or impractical to test experimentally in the field. In agriculture, numerous studies have utilized crop modeling to evaluate various projected climatic conditions (Stöckle & Kemanian, 2020). A wide variety of crop models are available for such studies, differing in their complexity and functionality. Models capable of realistically simulating the effects of elevated CO₂, temperature, and water stress on crop growth and development are essential for future climate change research (Peng et al., 2020).

Recent advancements in plant phenotyping, driven by high-throughput phenotyping tools, have significantly enhanced the accuracy and robustness of phenotype and allelic data collection. These innovations complement high-throughput genomic resources, allowing for a more precise understanding of plant traits under various conditions, including elevated CO₂ (Roychowdhury et al., 2024). The variations in field experiments induced by environmental factors like elevated CO₂ can now be mitigated using flexible, nondestructive robotic measurement platforms. These platforms, equipped with advanced navigation systems, multivariate sensors, and multiplot data acquisition capabilities, enable efficient and precise monitoring of crop performance. Furthermore, the combined effects of biotic and abiotic stresses, particularly under elevated CO₂ conditions, can be addressed through prediction models integrated with strategies like integrated pest management (Shafiq et al., 2024). Advances in crop and physiological models, such as those used in chickpea studies to identify region-specific constraints and yield gaps, have proven valuable in understanding the effects of climate change on crop productivity. These modeling innovations play a crucial role in addressing challenges related to sustainable food production, nutrition, and natural resource management under changing climate conditions, which is anticipated to be marked by escalated CO₂ levels (Palit et al., 2020).

16.6 Implications for agriculture and ecosystem functioning

The increase in atmospheric CO₂ levels is projected to reach up to 800 ppm by the end of the 21st century. It has significant implications for plant growth, physiology, and agricultural practices. It is interesting to understand that how elevated CO₂ affects plant productivity, adaptation strategies for crop breeding, and the broader impacts on ecosystems and carbon sequestration.

- 1. Improving resistance to drought:** As climate change makes water availability more unpredictable, it is imperative to breed crops for increased drought tolerance. Plants can obtain deeper soil moisture when the root biomass and depth are stimulated by elevated CO₂ (Uddin et al., 2018). Crop breeding capitalizes on this effect by concentrating on:
 - a. Root architecture:** Developing crops with bigger, more effective root systems that can reach deeper soil layers to absorb water is known as “root architecture” (Berntson & Woodward, 1992; Uddin et al., 2018).
 - b. Efficiency of water use:** By lowering the stomatal conductance, elevated CO₂ preserves or improves photosynthesis while reducing the water loss through transpiration. Drought

resistance can be increased by breeding crops with features that work in concert to provide this effect (Liu et al., 2022).

- c. **Molecular methods:** The WUE can be further increased by identifying and integrating drought-resistant genes, such as those controlling aquaporins (water channel proteins) (Fahad et al., 2017).
- 2. Increasing the efficiency of nutrient use:** By decreasing the nitrogen (N) concentrations in plant tissues, rising CO₂ levels might worsen nutritional limits and call for breeding techniques to maximize nutrient usage.
 - a. **Nitrogen-use efficiency (NUE):** In order to preserve the photosynthetic capacity and productivity, it is essential to target genes and characteristics that increase the NUE. It involves choosing genotypes with high photosynthetic nitrogen usage efficiency, in which plants assimilate more carbon per unit of nitrogen in their leaves. (Ainsworth & Rogers, 2007).
 - b. **Phosphorus uptake:** The availability of phosphorus restricts agricultural productivity, particularly in soils with low nutrient levels. The goal of breeding is to increase the organic acid exudation from the roots, which improves the solubility and uptake of phosphorus (Richardson et al., 2009).
 - c. **Micronutrient acquisition:** Changes in soil microbial interactions due to elevated CO₂ impact the cycling of nutrients. There is a growing emphasis on cultivating varieties with characteristics that facilitate the efficient uptake and utilization of micronutrients (Zhang et al., 2024).
- 3. Enhancing stress resilience:** To combat temperature fluctuations and other abiotic stressors intensified by climate change, breeders are developing resilient crop varieties that can thrive under combined elevated CO₂ and stress conditions.
 - a. **Heat stress mitigation:** By sustaining higher photosynthetic rates, elevated CO₂ can partially counteract the adverse effects of high temperatures. By choosing heat-tolerant features like the improved stability of photosynthetic enzymes like Rubisco, breeding efforts seek to optimize this benefit (Raza et al., 2019).
 - b. **Disease and pests resistance:** Variations in atmospheric CO₂ can change the dynamics of pathogens and pests. To protect crop production, it is essential to incorporate resistance genes using CRISPR technology and marker-assisted selection.
 - c. **Multistressor tolerance:** To create crops that can endure heat, drought, and nutritional stress while taking advantage of elevated CO₂ conditions, modern breeding programs are increasingly incorporating multi-trait selection.

Crop breeding programs emphasize these tactics in an effort to maximize the advantages of increasing CO₂ levels while reducing the dangers associated with nutrient constraints, water scarcity, and stressors brought on by climate change.

16.7 Ecosystem dynamics and agricultural management strategies

The increasing levels of atmospheric CO₂ have far-reaching effects that extend beyond boosting the agricultural productivity, influencing ecosystem functions and carbon storage mechanisms. Plants are central to these processes, capturing and storing atmospheric carbon through photosynthesis. Higher CO₂ levels accelerate the plant growth, which can enhance the accumulation of organic carbon in soils.

However, these impacts are intricately linked to broader ecosystem dynamics and agricultural management strategies.

16.8 Carbon storage in soils

One of the most important carbon storage systems, soils are essential for reducing the effects of climate change. More plant biomass is encouraged by elevated CO₂, which expands the amount of organic matter that soils can hold. Particularly successful methods for enhancing soil carbon storage include conservation tillage and cover crops. While cover crops add organic matter that breaks down into stable carbon forms in the soil, conservation tillage reduces the soil disturbance and carbon loss. By increasing the microbial activity, nutrient availability, and water retention, these techniques not only sequester carbon but also improve the soil quality. Global adoption of such methods might greatly reduce greenhouse gas emissions from agricultural areas, supporting the goal of carbon neutrality. For instance, emphasize the advantages of these methods in fostering soil health and serving as a natural means of lowering emissions.

16.9 Ecosystem dynamics and biodiversity

By changing the makeup of plant species and nutrient cycles, rising CO₂ levels also significantly impact ecosystems. More biomass and photosynthesis can produce more resources for wildlife, which could lead to increased biodiversity. However, ecological imbalances may also result from this. Invasive or fast-growing plants are examples of species that may predominate in an environment with high CO₂, outcompeting native species and lowering ecological stability overall ([Masters & Norgrove, 2010](#)). Moreover, changes in plant productivity and development can interfere with the cycling of nutrients. Increased CO₂ frequently improves carbon inputs into soils through root exudates and leaf litter. But this can lead to a mismatch in the availability of nutrients, especially phosphorus and nitrogen, which are essential for maintaining long-term productivity. The capacity of ecosystems to function as efficient carbon sinks may be compromised by such imbalances, particularly in nutrient-deficient environments ([Ainsworth & Long, 2021](#)).

The interaction of soil carbon storage, plant growth, and increasing CO₂ highlights the necessity of a comprehensive strategy to land management. It is essential to combine sustainable farming methods with laws meant to preserve biodiversity and improve ecosystem services. Addressing future difficulties will require continued research into nutrient cycling, species-specific reactions to increasing CO₂, and the possibility of long-term soil carbon storage. In summary, while rising CO₂ levels offer potential benefits such as improved plant growth and efficiency, they also bring challenges that demand careful planning and innovation. Adapting crop breeding techniques and refining management practices are essential for leveraging these opportunities effectively. By understanding these complex dynamics, we can enhance food production systems while minimizing the adverse effects of climate change.

16.10 Knowledge gaps and future directions

The study of plant responses to elevated CO₂ has made significant progress; however, several knowledge gaps remain that must be addressed to enhance our understanding of plant physiology, productivity, and resilience under changing climatic conditions. The idea that elevated CO₂ levels have long-term beneficial effects on plant productivity is being reconsidered, as the photosynthetic fertilization effect is often short term and not always consistent across major crop species. The Intergovernmental Panel on Climate Change's 2018 special report emphasizes the need for effective policy strategies to limit greenhouse gas emissions, acknowledging that the potential benefits of elevated CO₂ on crop growth may be less sustainable than initially believed. To effectively address the challenges posed by rising atmospheric CO₂ concentrations, it is crucial for the scientific community to develop comprehensive and time-tested research outcomes. In this context, an integrated research framework that combines multiple biological disciplines such as plant physiology, genomics, ecology, and climate science is essential for gaining a deeper understanding of how crops and ecosystems will respond to long-term elevated CO₂ levels. Such interdisciplinary approaches will provide a robust foundation for informed strategies to ensure agricultural resilience and sustainability in the face of climate change.

From a molecular perspective, the regulatory networks and signaling pathways that govern plant responses to elevated CO₂ remain inadequately characterized. While transcriptomics, proteomics, and metabolomics have provided insights into the genes, proteins, and metabolites involved, integration of these datasets into a cohesive systems biology framework is still lacking (Salas Fernandez et al., 2017). A deeper understanding of the epigenetic and posttranslational modifications under elevated CO₂ could reveal novel targets for crop improvement. Additionally, the role of noncoding RNAs and their regulatory influence in CO₂ responses is an emerging area that warrants more attention (Varshney et al., 2018).

Another significant gap lies in the limited use of advanced phenotyping tools under realistic field conditions. Controlled environment studies, while valuable, do not fully replicate the dynamic and heterogeneous conditions of natural ecosystems. Technologies such as high-throughput phenotyping platforms, remote sensing, and imaging tools have the potential to capture phenotypic traits with greater precision and under variable environmental conditions. These innovations, coupled with artificial intelligence and machine learning, could facilitate the rapid identification of traits associated with CO₂ resilience and their incorporation into breeding programs. Future directions must also prioritize the development of more robust crop models that integrate genotype-by-environment-by-management (G×E×M) interactions under elevated CO₂ scenarios. These models should incorporate data from long-term experiments, such as FACE studies, to improve the predictions of crop productivity and resource use efficiency. Furthermore, global collaboration is needed to establish open-access databases that combine molecular, physiological, and environmental datasets, enabling researchers to address questions at multiple scales (Aggarwal et al., 2018). Policy and societal dimensions also demand attention.

The implementation of research findings into practical agricultural strategies will require engagement with policymakers, farmers, and stakeholders. Public perception of technologies such as genetic modification and genome editing remains a significant barrier to their adoption. Effective communication and education campaigns are necessary to build trust and acceptance of these tools in addressing food security challenges.

16.11 Conclusion

The rising levels of atmospheric CO₂ represent a pivotal factor influencing plant biology, with far-reaching implications for agriculture, ecosystems, and global food security. This chapter has underscored the complex interplay of elevated CO₂ with plant physiological and biochemical processes, highlighting both opportunities and challenges. Enhanced photosynthesis and biomass production offer potential benefits for crop yields; however, these gains are tempered by trade-offs in nutritional quality, stress resilience, and interactions with environmental constraints such as nutrient limitations, ozone, and water availability. Advances in experimental methodologies, such as FACE systems and omics technologies, have provided invaluable insights into the mechanistic and adaptive responses of plants under elevated CO₂ conditions. These tools, combined with predictive modeling, offer robust frameworks for designing crops and ecosystems resilient to future climatic scenarios. Nevertheless, critical knowledge gaps remain, particularly concerning the long-term and multi-factorial impacts of elevated CO₂ on plant systems and ecosystem functioning. To address these challenges, an interdisciplinary approach integrating molecular biology, ecology, and agronomic practices is essential. Furthermore, translating research insights into actionable strategies for crop breeding, carbon sequestration, and biodiversity conservation will be key to mitigating the adverse effects of climate change. As we navigate an era of unprecedented environmental change, leveraging elevated CO₂ as a driver for sustainable agriculture and ecosystem management remains both a scientific imperative and a societal necessity.

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Agrochemicals: harmful and beneficial effects of climate change scenarios

17

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17.1 Introduction

The agricultural sector, the backbone of global food security, has witnessed remarkable transformations through the strategic use of agrochemicals (Swatson et al., 2024). These substances, encompassing fertilizers, pesticides, plant growth regulators (PGRs), and soil amendments, have played a pivotal role in enhancing agricultural productivity, protecting crops from pests and diseases, and improving soil health (Rastogi et al., 2023). Agrochemicals, especially during the Green

Revolution, were instrumental in addressing food shortages and meeting the demands of a rapidly growing population. However, the escalating global population—projected to reach 9.7 billion by 2050—places unprecedented pressure on agricultural systems to sustainably produce sufficient food while facing challenges posed by the climate change (Ullah et al., 2024).

Climate change, characterized by significant shifts in meteorological variables such as temperature, precipitation patterns, and the frequency of extreme weather events, has emerged as a critical global issue. Anthropogenic activities, including deforestation, industrialization, and intensive agricultural practices, have contributed to the elevated concentrations of greenhouse gases like carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) (Filonchyk et al., 2024). These emissions have intensified the greenhouse effect, leading to a rise in global temperatures and triggering extreme climatic events such as droughts, floods, and cyclones. Such events disrupt agricultural systems, threatening food security and economic stability (Kumar et al., 2024). The agricultural sector is particularly vulnerable to these climatic shifts, given its dependence on favorable weather conditions and natural resources.

In this context, agrochemicals occupy a dual role—both as potential mitigators and contributors to climate change impacts. On the one hand, they enhance crop productivity and resilience against biotic and abiotic stresses, which is essential for sustaining food production under changing climatic conditions (Das, 2024). Fertilizers improve the soil nutrient availability, pesticides safeguard crops from pests and diseases, and PGRs optimize plant development, contributing to higher yields despite adverse weather conditions (Gupta et al., 2024). On the other hand, the overuse or improper application of agrochemicals poses significant environmental and health risks. Excessive reliance on fertilizers and pesticides contributes to greenhouse gas emissions, degrades soil and water quality, and disrupts the ecological balance (Mitra et al., 2021).

Moreover, climate change directly influences the efficacy of agrochemicals. Rising temperatures, altered precipitation patterns, and increased incidences of extreme weather events can modify the behavior, persistence, and effectiveness of these chemicals (Koli et al., 2019). For example, higher temperatures may accelerate the degradation of pesticides, reducing their protective effects, while excessive rainfall may lead to nutrient leaching, undermining the efficiency of fertilizers. Simultaneously, climate change exacerbates pest pressures, disease outbreaks, and weed proliferation, necessitating an increased reliance on agrochemicals, which further intensifies the environmental footprint of agricultural systems (Yang et al., 2024).

Understanding the complex interplay between agrochemicals and climate change is imperative for developing sustainable agricultural practices. This chapter explores the dualistic role of agrochemicals under changing climate scenarios, highlighting their beneficial and harmful effects. It also examines the changing efficacy of agrochemicals in response to climatic variations and underscores the need for innovative strategies to optimize their use. By striking a balance between productivity and sustainability, agrochemicals can be harnessed as a tool to mitigate the adverse

impacts of climate change while minimizing environmental and health risks, ultimately contributing to a resilient agricultural system.

17.2 Agrochemicals and their role in agriculture

Agrochemicals play an essential role in enhancing agricultural productivity, ensuring balanced soil nutrients, and maintaining soil health while protecting crops from various infections. This, in turn, significantly boosts crop yields. Historically, the large-scale use of agrochemicals has been instrumental in meeting the growing global demand for food, particularly during the Green Revolution in many developing countries. This period witnessed a dramatic rise in agricultural production, reaching levels several times higher than before (Meena et al., 2020). The global population, currently at 7.2 billion, is projected to increase to 9.3 billion by 2050 (FICCI, 2016; Meena, 2017; Meena et al., 2016). This population growth will inevitably intensify the demand for agrochemicals to ensure sufficient food and feed supply. Consequently, a sustainable approach to agriculture becomes imperative, where the judicious and efficient use of agrochemicals remains a critical component in addressing future food security challenges.

Agrochemicals, based on their intended purposes, can be broadly categorized into four groups: plant protection chemicals (pesticides), plant growth-promoting chemicals (fertilizers), PGRs (including hormones, stimulants, retardants, and additives), and other related chemicals such as feed additives, antibiotics, and veterinary drugs (FICCI, 2019). A comprehensive list of various agrochemicals utilized in agriculture is presented in Table 17.1. These agrochemicals play a crucial role at various stages of plant growth, aiding in their development and protection against infections caused by living organisms. Additionally, specific chemicals are utilized in smaller quantities to regulate or stimulate plant growth, as well as to enhance and maintain nutrient availability in the soil. Furthermore, agrochemicals also include nutrient additives for animal feed, antibiotics, and veterinary drugs, expanding their scope of application (Gupta et al., 2019).

Pesticides, such as dichlorodiphenyltrichloroethane (DDT) and hexachlorocyclohexane (HCH), have been widely used to combat agricultural pests and control human disease vectors. Their primary role is to manage weeds and insects (Sharma et al., 2019). Pesticides are classified based on their target species, chemical composition, mechanisms of action, and potential health impacts. They can also be categorized according to their application conditions and other factors (Hashimi et al., 2020; Jayaraj et al., 2016). Chemically, pesticides are grouped into microbiological pesticides, carbamates, pyrethroids, organochlorines, organophosphates, growth regulators, and neonicotinoids, with examples including DDT, 2,4-D, HCH, dieldrin, fluvalinate, coumaphos, chlorothalonil, and chlorpyrifos (Lushchak et al., 2018; Zhu et al., 2014). Globally, approximately 2 million tons of pesticides are used annually, with herbicides accounting for 48%, insecticides 30%, fungicides 18%, and other pesticides 6% (De et al., 2014; Hashimi et al., 2020). Recent forecasts predict that global pesticide usage will rise to nearly 3.5 million tons this year (Zhang, 2018).

Table 17.1 Classification and examples of various agrochemicals used in agriculture, including fertilizers, pesticides, plant growth regulators, and soil conditioners.

Types of agrochemicals		
Fertilizers	Example	References
Nitrogen-based	Urea, ammonium nitrate	Zaman et al. (2015)
Phosphorus based	Superphosphate, diammonium phosphate	Schröder et al. (2010)
Potassium based	Potash	Delgado et al. (2024)
Micronutrient fertilizers	Zinc sulfate, boron compounds	Hignett and McClellan (1985)
Pesticides		
Insecticides	Organochlorines, organophosphates, and carbamates.	Bradley (1910)
Herbicides	Borax, copper sulfate, ammonium sulfate, 2,3,6 terbutylazine (TBA), dicamba, and tricamba	Scott and Scott (1962)
Fungicides	Bordeaux mixture, copper oxychloride, chloropicrin, formaldehyde, and vapam,	Gupta (2022)
Rodenticides	Difenacoum, bromadiolone, and brodifacoum	Koli et al. (2019)
Molluscides	Metal salts such as iron(III) phosphate, aluminum sulfate	Koli et al. (2019)
Nematicides	Aldicarb	Koli et al. (2019)
Acaricides	Chlorinated hydrocarbons, carbamates, dicofol	Koli et al. (2019)
Plant growth regulators		
Growth promoters	IAA, GA, CK, C ₂ H ₂ , ABA	Koli et al. (2019)
Growth Retardants	Chlormequat chloride (CCC)	Koli et al. (2019)
Soil conditioner chemicals used in animal husbandry pesticides		
Antibiotics	Actidione, griseofulvin, streptomycin, streptocycline, etc.	Koli et al. (2019)
Hormones	indole-3-acetic acid, GA, CK, C ₂ H ₂ , abscisic acid	Koli et al. (2019)

Major pesticide-consuming countries include the United States, China, India, Italy, Argentina, Japan, Thailand, France, Brazil, and Canada (Amber, 2017). China leads in global pesticide production and predominantly applies them to rice crops. Between 1991 and 2006, China's pesticide usage surged from 76 to 146 million tons. Japan, with the largest pesticide market in Asia, is also among the top global consumers of

pesticides (Zhang et al., 2011). Africa, however, remains the region with the lowest pesticide use, accounting for only 2% of global consumption, according to the Food and Agriculture Organization (FAO) estimates (Abate et al., 2000). During the mid-20th century, organochlorine pesticides were extensively used to control diseases like malaria and typhus. However, their persistence in the environment led to widespread bans or significant restrictions in most developed countries over the last five decades. This shift resulted in the adoption of organophosphate pesticides, followed by carbamates in the 1970s and pyrethroids in the 1980s. Over time, the development and application of various other pesticides have contributed to effective pest management, reducing pest-related risks and significantly improving agricultural productivity (Mahmood et al., 2014).

Insecticides are substances designed to kill or inhibit the growth and reproduction of insects. They are widely used in agriculture, as approximately 67,000 insect species are known to cause significant losses in agricultural yields worldwide (Campos et al., 2019). India ranks as the 12th largest producer of insecticides globally, manufacturing over 90,000 tons annually (Khan et al., 2010). Insecticides can be categorized based on their mode of action and function, including chemosterilants, growth regulators, hormones, pheromones, disinfectants, attractants, and desiccants (Sparks & Nauen, 2015). Their primary purpose is to eliminate insects that pose threats to agriculture by feeding on growing crops, consuming stored food, or transmitting diseases to livestock. The extensive use of insecticides plays a crucial role in safeguarding agricultural production and ensuring food security.

Herbicides are agrochemicals specifically designed to reduce or inhibit the growth of unwanted herbs and weeds that compete with crops for nutrients and fertilizers in the soil. By depleting these essential resources, weeds can hinder the growth and yield of cultivated crops. Herbicides work selectively, targeting weeds while sparing the main crops, thereby enabling their safe application for weed control in agriculture. Herbicides are classified based on their chemical composition, specificity, and timing or mode of application (Peterson et al., 2013). Glyphosate is the most commonly used herbicide, followed by metolachlor-S and atrazine (Sharma et al., 2019). Globally, herbicides like glyphosate, 2,4,5-trichlorophenoxyacetic acid (2,4,5-T), atrazine, hexazinone, simazine, alachlor, butylate, and paraquat account for approximately 50% of all pesticide usage, making them a rapidly growing segment of the pesticide industry (Lushchak et al., 2018). Paraquat, often called “gramoxone,” is a fast-acting, nonselective herbicide that effectively destroys green weeds. Its redox activity generates superoxide anions, which deplete antioxidant pools and produce secondary metabolites, contributing to its toxicity in both humans and animals (Madheshiya et al., 2023; Omar et al., 2022). Another noteworthy herbicide, acolbifene, belongs to the diphenyl ether class and offers broad-spectrum weed control while being safe for soybean crops, making it highly effective in soybean farming. Atrazine, a chlorinated triazine systemic herbicide, selectively targets annual grasses and broadleaf weeds, primarily before they emerge. It is widely applied to crops such as field corn, sweet corn, sorghum, and sugarcane. Similarly, 2,4-dichlorophenoxyacetic acid is a commonly used herbicide that controls broadleaf weeds in a variety of field, fruit, and vegetable crops (Cerdeira, 2021; Omar et al., 2022). These herbicides play a pivotal

role in modern agriculture by enhancing the crop productivity and reducing competition from weeds.

Fungicides are synthetic agrochemicals widely used by farmers to control the growth of fungi that damage crops and reduce overall yields. As a specialized group of pesticides, fungicides work by preventing, repeling, or destroying phytopathogenic fungi. Their mode of action targets specific metabolic pathways in fungi, making them effective in mitigating fungal diseases in agricultural fields (Lushchak et al., 2018). Fungicides are classified into various chemical groups, including phthalimides, carbamic acid derivatives, halogenated substituted monocyclic aromatics, benzimidazoles, and organomercury compounds. Examples of commonly used fungicides include diflolan, metalaxyl, carbenazin, kitazin, and oxafun-T (Balba, 2007). These fungicides play a crucial role in safeguarding crop health and enhancing agricultural productivity by preventing fungal infections.

Organic or inorganic substances added to enhance soil structure, quality, water retention, and nutrient content are referred to as soil supplements or amendments. These substances improve the crop quality and overall yield by optimizing the nutrient uptake and modifying the root microenvironment. Soil supplements, such as fertilizers, hormones, and growth promoters, support plant growth and development by boosting the metabolic and reproductive pathways when applied to the soil (Dhanker et al., 2021).

17.3 Climate change scenarios: an overview and their impact on agriculture

Global climate change has been evolved as one of the most critical concerns immoderately reshaping the Earth's ecosystem. Though the instances of natural climate change have always been witnessed by the world since time immemorial, but the pace of change has accelerated dramatically over the last decade (Malhi et al., 2021). Climate change can be defined as significant shifts in the average values of meteorological variables, such as precipitation and temperature that have been computed over an extended period of time (Koutsoyiannis, 2021). Over the last few decades, there have been substantial global climate fluctuations that can be attributed to increased anthropogenic activities that have changed the composition of the atmosphere (Abbass et al., 2022). Since 1750, the concentrations of greenhouse gases like methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) have increased by 150%, 40%, and 20%, respectively. Emissions of CO_2 , the largest contributor to greenhouse gas emissions, increased from 22.15 billion metric tons in 1990 to 36.14 billion metric tons in 2014 (Mehmood et al., 2022). According to projections, if current trends in deforestation, greenhouse gas emissions, and soil, water, and air pollution continue unchecked, the current increasing trends might reach or surpass 1.5°C by 2050 (UN ESCAP, 2021). The increasing concentration of greenhouse gases has further ramifications for the escalating global temperature. By trapping the thermal radiation released by the surface of the Earth and atmosphere, these infrared-active gases mainly CO_2 , O_3 , and water vapor lead to the phenomenon of greenhouse

effect (Shah et al., 2024). Thus, reducing greenhouse gas emissions is imperative in order to restrict the rise in global temperatures to 2°C above preindustrial levels. Since 2005, developed nations have contributed approximately 60%–80% to global temperature increases, sea ice loss, and upper-ocean warming, compared to 20%–40% contributed by developing nations. Globally, extreme climatic events like heat waves, droughts, floods, and unpredictable precipitation patterns have been further exacerbated by this unprecedented warming (Malhi et al., 2021).

Agriculture is the most vulnerable sector to climate change due to its enormous size and sensitivity to climatic conditions, leading to substantial economic impact. The Weather, Climate and Catastrophe Insight annual study states that natural disasters incurred global economic losses of US\$225 billion in 2018 (Azadi et al., 2021). Approximately 95% of these losses were caused by weather-related catastrophes that are directly tied to climate change, such as droughts, floods, and cyclones. These effects are especially noteworthy for the agricultural industry, which is the backbone of the world's economy and food production and is currently experiencing severe disruptions as a result rapidly changing climatic conditions (Arora, 2019). With the world's population expected to exceed 9.7 billion by 2050, agricultural lands will face increased pressure to supply rising food demand, notwithstanding climate-related concerns. A growing challenge to global food security is highlighted by the inextricable relationship between agriculture and climate change (Al-Amin et al., 2024). The World Food Programme reported in 2018 that crop yield increases per hectare are failing to keep pace with population growth. Similarly, data from the FAO in 2016 indicated that if current trends in greenhouse gas (GHG) emissions and climate change persist, the production of staple cereals could decline significantly by 2100, with maize yields dropping by 20%–45%, wheat by 5%–50%, and rice by 20%–30%. Such reductions in crop yields could result in unprecedented losses, driving up food prices and exacerbating challenges in meeting the demands of the growing global population (Arora, 2019). The escalating demand for food, driven by population growth, has intensified agricultural practices characterized by the excessive use of agrochemicals, overexploitation of water resources, and an increased livestock production. These practices not only contribute to GHG emissions but also degrade natural resources, exacerbating environmental pollution (Gupta et al., 2024).

17.4 Beneficial effects of agrochemicals and improved resilience to stressors in a changing climate

The agricultural sector is increasingly confronted with multifaceted challenges arising from climate change, which exacerbate the frequency and intensity of both abiotic and biotic stressors. Abiotic stressors, such as prolonged droughts, heightened soil salinity, and extreme temperature fluctuations, disrupt physiological processes in plants, reducing their growth and productivity. (Anjum et al., 2011; Bitá & Gerats, 2013; Chaudhry & Sidhu, 2022; Rai et al., 2021). Simultaneously, biotic stressors, including pest outbreaks and the proliferation of plant diseases, compound these

threats, leading to significant yield losses (Savary et al., 2019). The compounded impact of these stressors jeopardizes global food security and the economic viability of farming systems, especially in vulnerable regions. In this context, agrochemicals emerge as vital tools for mitigating the adverse effects of such stressors (Dhananjayan et al., 2020). Cooper and Dobson (2007) delineated 26 primary benefits, which are immediately evident, and 31 secondary advantages, characterized by their long-term impact or subtle nature, associated with conventional pesticide use some of which are listed in (Fig. 17.1). Key benefits encompass enhanced crop productivity, elevated food safety standards, improved human health, and overall quality of life, alongside reductions in labor intensity, energy consumption, and environmental deterioration (Cooper & Dobson, 2007). When employed with precision and care, they play a pivotal role in enhancing the resilience of crops by fortifying their ability to withstand and recover from environmental and biological pressures. For instance, fertilizers supply essential macro- and micronutrients that improve plant vigor and strengthen stress tolerance mechanisms, such as nutritional stress (Muneer et al., 2024). Pesticides and fungicides shield crops from invasive pests and pathogens, preserving the yield and quality even in challenging conditions (Boruah et al., 2023). Agrochemicals, thus bolster the adaptive capacity of agricultural systems by supporting the development of robust and sustainable cropping practices. By improving the nutrient use efficiency, optimizing growth dynamics, and protecting crops from environmental and biological adversities, agrochemicals contribute to the broader goals of sustainable agriculture, ensuring food security while mitigating resource depletion.

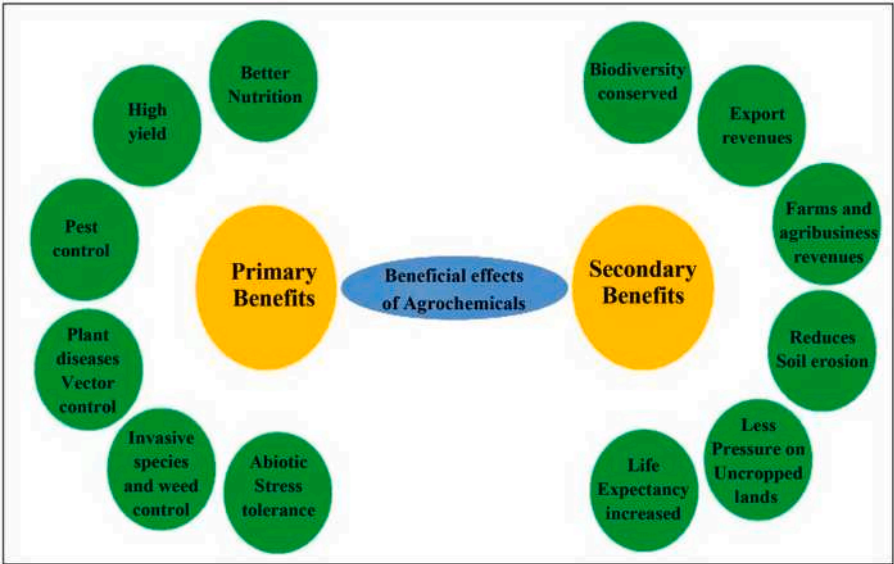


Figure 17.1 Illustration showing the beneficial effect of agrochemicals.

17.4.1 Role in enhancing the abiotic stress tolerance

Drought is recognized as a critical abiotic stressor with the potential to severely constrain crop productivity (Al-Ashkar et al., 2021; Roy et al., 2021). The application of agrochemicals such as nanoparticles (NPs) serves as a viable strategy to mitigate drought-induced stress by enhancing antioxidant enzyme activity, modulating phytohormone concentrations, and influencing key physiological processes. Similarly, the application of Cu and Zn NPs in wheat enhances antioxidant enzyme activity and relative water content, decreases thiobarbituric acid levels, modulates reagent precipitation, stabilizes photosynthetic pigment concentrations in leaves, and alleviates the adverse effects of stress (Semida et al., 2021; Taran et al., 2017). Moreover, organic manures significantly enhance the activities of catalase, peroxidase and superoxide dismutase enzymes while reducing the malondialdehyde and H₂O₂ levels, thereby improving drought tolerance (Hussain & Shah, 2023). Bhanwaria et al. (2022) demonstrated that organic amendments enhance the nutrient and water uptake, stimulate the antioxidant activity, promote chlorophyll biosynthesis, and facilitate osmolyte accumulation, collectively contributing to improved plant growth and yield under drought stress. Research indicates that, in addition to mitigating drought stress, the application of agrochemicals, fertilizers, and various plant growth-promoting compounds such as abscisic acid and jasmonic acid also alleviates salinity, ozone, and heavy metal stress (Khadri et al., 2006; Lin et al., 2001; Wilkinson & Davies, 2010). Similarly, under elevated ozone conditions, ethylene-diurea (EDU) has been documented to mitigate oxidative stress in plants. Elevated ozone induces the generation of reactive oxygen species (ROS), leading to cellular damage, reduced photosynthetic efficiency, and impaired growth. EDU acts as a protective agent by enhancing antioxidant defense mechanisms, stabilizing cellular structures, and preserving metabolic functions. By reducing the ROS accumulation, EDU effectively alleviates ozone-induced oxidative damage, safeguarding physiological processes such as chlorophyll synthesis and stomatal regulation (Tiwari et al., 2005; Tiwari, 2017).

17.4.2 Improved resilience to stressors (pests, insects, etc.) in a changing environment

Agrochemicals provide an immediate and effective solution to control a wide range of pests and pathogens that compromise the crop health and yield.

17.4.2.1 Strengthening plant health

Fertilizers ensure optimal nutrient availability, enhancing plant vigor and making crops less susceptible to pest infestations. Nutrient-rich plants exhibit stronger cell walls and robust defense mechanisms.

17.4.2.2 Induction of systemic resistance

Certain agrochemicals, including biopesticides and plant activators, stimulate plants' systemic acquired resistance and induced systemic resistance, fortifying defenses

against pests and insects. Certain chemical agents effectively stimulate plant defense mechanisms, providing robust resistance against pests and pathogens. Salicylic acid (SA) and benzothiadiazole, well-known systemic acquired resistance activators, enhance the expression of defense-related genes such as PR-3.1 and PR-5, while also promoting the accumulation of endogenous SA to suppress fungal pathogens like *Magnaporthe oryzae* (Rahman, 2014). Similarly, silicon formulations act as chemically induced resistance activators by reinforcing structural barriers such as papillae formation and triggering the upregulation of defense-related genes, thereby strengthening penetration resistance (Pati et al., 2025). These chemical substitutes offer an efficient approach to mitigating disease impacts and improving crop resilience in sustainable agricultural practices.

17.4.2.3 *Climate-responsive pest and weed management*

Agrochemicals provide flexible solutions to manage pests whose life cycles, migration patterns, and population dynamics are altered by climate change, such as rising temperatures and unpredictable rainfall. Rising CO₂ levels and associated changes in global precipitation and temperature significantly threaten the weed management and agricultural production. These climatic shifts alter the distribution, population structure, lifecycle, and infestation intensity of plant pests, leading to increased crop vulnerability and reduced yields (Munda et al., 2024). Such changes exacerbate the competitive advantage of invasive weeds and pests, which thrive under variable climatic conditions, further complicating management strategies. Agrochemicals, including herbicides, insecticides, and fungicides, play a crucial role in mitigating these challenges. They can effectively control pest populations and suppress the weed growth, ensuring crop protection and stabilizing yields. Variable rainfall exerts a profound influence on insect populations. Staley et al. (2007) investigated the impact of elevated summer rainfall and drought on the soil-dwelling wireworm (*Agriotes lineatus* L.) in grassland plots. Wireworms are highly destructive pests affecting crops like potatoes, corn, and sugar beet, particularly when cultivated in grassland settings. Projections suggest that climate change will exacerbate their prevalence and damage potential (Johnson et al., 2008). The study revealed accelerated proliferation of wireworm populations in the upper soil layers under increased summer rainfall compared to ambient and drought conditions. Furthermore, moisture loss during plant transpiration induces cavitation within xylem water columns, generating ultrasonic acoustic emissions that attract deleterious bark beetles (Scolytidae). Several studies have reported that potassium-enriched fertilizers can mitigate such pest-induced stress by enhancing the plant resilience and reducing pest attraction (Bustamante, 1998; Chen, 2014).

17.4.2.4 *Integrated pest management*

The judicious use of pesticides in combination with cultural and biological methods enhances pest control efficacy while mitigating risks associated with climate-induced pest outbreaks.

17.4.2.5 Biofortification for defense

Fertilizers enriched with micronutrients like silicon, zinc, and potassium strengthen the plants' natural pest resistance by enhancing structural barriers and biochemical defenses. Balanced nutrient levels, especially potassium and phosphorus, indirectly strengthen the plant resistance to various insect pests through biochemical, physical, and mechanical mechanisms (Rajareddy et al., 2024).

17.4.3 Role in increasing the yield and reducing crop losses

Agrochemicals, including fertilizers, pesticides, herbicides, and fungicides, play a pivotal role in enhancing the agricultural productivity and minimizing the crop losses. Fertilizers supply essential nutrients like nitrogen, phosphorus, and potassium, promoting vigorous plant growth, improving photosynthesis, and boosting yields. Pesticides and insecticides effectively control pests and insects that would otherwise damage crops, thereby preserving plant health and reducing yield losses. Herbicides manage weed populations, preventing competition for resources such as nutrients, water, and sunlight, allowing crops to thrive. Fungicides effectively control fungal infections, which are major contributors to significant yield reductions and quality deterioration, thereby enhancing the productivity in rice cultivars (Kumar et al., 2024).

Moreover, the targeted application of agrochemicals improves the resource efficiency, ensuring that crops achieve their genetic potential even under biotic and abiotic stress conditions. Modern formulations, such as slow-release fertilizers and bio-based pesticides, further enhance their efficacy while reducing environmental risks. By integrating agrochemicals with sustainable practices like precision farming and integrated pest management, agricultural systems can achieve higher productivity and resilience against global challenges such as climate change and pest outbreaks.

17.5 Harmful effects of agrochemicals under climate change scenarios

The escalating use of agrochemicals, particularly pesticides, presents significant environmental and health challenges, which are exacerbated by the impacts of climate change. Pesticides, primarily synthetic, are pervasive in ecosystems, and their toxic effects extend beyond target pests to include humans, livestock, and nontarget species. In the context of a changing climate, these risks are magnified due to altered pest dynamics, increased pesticide application rates, and enhanced chemical persistence in the environment. Climate change influences pesticide toxicity through multiple pathways. Rising temperatures, altered precipitation patterns, and extreme weather events can enhance the mobility of pesticides in soil and water systems, increasing the likelihood of contamination. These conditions also intensify surface runoff, transporting pesticides into aquatic ecosystems and causing bioaccumulation within trophic chains. Consequently, aquatic organisms face direct chemical exposure, which may extend to humans through water used for public consumption.

Such interactions underline the compounded risks to both ecosystems and public health in a warming world. Sustained pesticide exposure, aggravated by climate-driven factors, can lead to severe health consequences, including:

- Hormonal imbalances, such as infertility and breast-related issues.
- Neurological, psychological, and behavioral disorders.
- Reproductive system abnormalities.
- Immune system dysfunction and increased susceptibility to diseases.
- Blood-related disorders and genotoxicity, potentially altering genetic material.
- Elevated risks of cancer and neurodegenerative diseases.

Moreover, climate-induced shifts in pest populations and the emergence of invasive species may necessitate higher pesticide usage, compounding the risks of contamination in soil, water, and vegetation. Nontarget species, including pollinators, birds, and beneficial insects, are particularly vulnerable, with cascading effects on biodiversity and ecosystem services critical for climate resilience. Numerous studies highlight the toxicological and epidemiological risks associated with pesticides (Alengebawy et al., 2021; Hernández & Tsatsakis, 2017; Mostafalou & Abdollahi, 2017). Pesticide exposure has been strongly associated with severe health risks, including carcinogenicity, reproductive toxicity, immunotoxicity, and neurodegenerative disorders. Studies have demonstrated that chronic exposure to these chemicals can disrupt critical biological systems, posing risks to both human and environmental health (Fenga et al., 2021; Sarailoo et al., 2022). These risks are amplified under climate-altered scenarios, where prolonged exposure becomes more likely.

Despite their benefits, such as improving crop yields and controlling disease vectors, the intensified use of pesticides under climate stressors underscores the urgent need for sustainable agricultural practices. Integrated pest management (IPM), agroecological approaches, and climate-resilient cropping systems must be prioritized to reduce the reliance on agrochemicals while mitigating their amplified environmental and health impacts in the face of climate change.

17.5.1 Environmental risks: soil degradation, water contamination, and the impact on nontarget organisms

17.5.1.1 Water contamination and impact on nontarget organisms

Pesticide contamination in surface and groundwater presents a significant threat to aquatic ecosystems and public health, driven by the extensive use of agrochemicals in agriculture. Global monitoring studies have consistently detected critical contaminants, including atrazine, metolachlor, chlorpyrifos, tebuconazole, and other pesticides, at alarming concentrations in aquatic environments. For instance, diuron concentrations range from 0.03 to 22,770 ngL⁻¹, dimethoate from 0.57 to 61,200 ngL⁻¹, and carbendazim from 0.04 to 2239 ngL⁻¹ (de Souza et al., 2020). These high levels of contamination exemplify the pervasive impact of pesticide overuse on water quality and ecosystem integrity. Surface waters are particularly susceptible to pesticide contamination due to surface runoff during rainfall or irrigation, as well

as spray drift from agricultural fields (Reichenberger et al., 2007; Zhang et al., 2018). The accumulation of these chemicals in aquatic ecosystems leads to persistent environmental damage, exacerbated by climate change factors such as increased rainfall intensity and altered hydrological patterns, which enhance the leaching and transport of pesticides. Pesticides also infiltrate groundwater through percolation, improper disposal, spills, and leakages, further compromising the water quality (Shaikh & Birajdar, 2024).

17.5.1.2 *Impact on aquatic organisms*

The ecological consequences of pesticide contamination are profound. Aquatic vegetation, responsible for approximately 80% of dissolved oxygen in aquatic systems, is often destroyed by herbicides, causing hypoxia, fish asphyxiation, and reduced fish productivity (Riaz et al., 2021). The disruption of aquatic food webs and biodiversity is a recurring outcome, as low concentrations of pesticides, such as malathion, alter plankton populations and consequently affect tadpole growth (Staley et al., 2015; Zaller, 2020). Herbicides like glyphosate and insecticides such as chlorpyrifos and endosulfan are particularly harmful to amphibians, causing high mortality rates and physiological disruptions (Kenko, 2022; Lehman & Williams, 2010; Relyea, 2005; Sparling & Fellers, 2009). Amphibians are especially vulnerable to pesticide exposure, with atrazine linked to endocrine disruption and reproductive abnormalities (Bishop et al., 2010; Pinelli et al., 2019). Ten percent of male frogs exposed to atrazine-contaminated water developed hermaphroditic traits, including the formation of ovaries within their testes and altered mating behaviors (Thammachoti, 2012). Such endocrine-disrupting effects underscore the broader implications of pesticide contamination on non-target organisms. In fish nurseries, herbicide applications near weedy areas reduce vegetative shelter, exposing juvenile fish to predators and undermining reproductive success (Zaller, 2020). These disruptions extend to amphibians, where carbaryl has been shown to be toxic to multiple species, and glyphosate causes significant mortality in tadpoles and juvenile frogs (Relyea, 2005). Moreover, complex mixtures of pesticides in surface waters often exhibit additive or synergistic interactions, amplifying toxicity and complicating risk assessments.

17.5.1.3 *Impact on terrestrial organisms*

The pervasive use of pesticides has not spared terrestrial animal populations, inflicting significant harm on various beneficial species. Broad-spectrum insecticides, including carbamates, organophosphates, and pyrethroids, have caused substantial declines in populations of pollinators such as bees and beetles. Studies indicate that insect populations thrive more robustly on organic farms compared to conventional ones due to reduced pesticide exposure. Furthermore, the synergistic effects of pyrethroids with triazole or imidazole fungicides exacerbate the toxicity to honeybees, impairing their survival (Belzunces et al., 2012; Yadav et al., 2024). Neonicotinoid insecticides like clothianidin and imidacloprid are particularly toxic to bees; even minimal doses of imidacloprid have been shown to disrupt foraging

behavior (Pereira et al., 2020) and reduce cognitive abilities like learning (Schwartz et al., 2020) leading to a catastrophic decline in honeybee populations, particularly at the start of the 21st century. This decline poses a grave threat to global food production, as nearly one-third of crops rely on pollination services provided by bees. Residues of pesticides, especially neonicotinoids, have been detected in honey and wax from commercial hives, further underscoring the widespread contamination of the ecosystem.

Bird populations have also suffered significant declines, with estimates suggesting a reduction of 20%–25% since pre-agricultural times. Pesticide exposure is now recognized as a primary contributor to this loss, particularly through bioaccumulation in tissues, which leads to mortality (Fig. 17.2). For instance, the decline in bald eagle populations in the United States was largely attributed to exposure to DDT and its metabolites (Colborn, 1991; Dykstra et al., 2019). Fungicides further contribute to the decline of avian and mammalian populations by decimating soil invertebrates, such as earthworms, which serve as key food sources. Granular pesticides are often mistaken for food grains by birds, leading to poisoning, especially in raptors exposed to highly toxic organophosphate insecticides. Sublethal doses of pesticides can disrupt the nervous system of birds, resulting in behavioral abnormalities (Walker, 2003).

17.5.1.4 Soil degradation

Excessive reliance on agrochemicals has precipitated severe soil degradation by disrupting its intricate biological and physicochemical equilibrium. Persistent pesticide residues, alongside the overuse of synthetic fertilizers, compromise the soil microbial diversity, undermining critical processes such as nitrogen fixation,

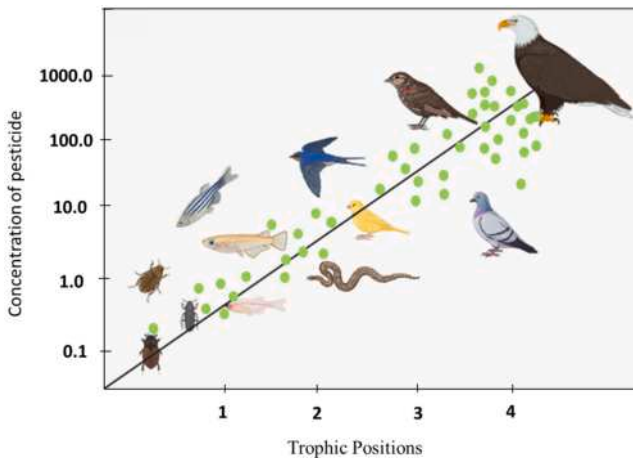


Figure 17.2 Figure illustrating the bioaccumulation of agrochemicals (contaminants) across different trophic levels.

organic matter decomposition, and nutrient cycling. Herbicides like glyphosate impede nitrogen-fixing bacteria, while fungicides diminish mycorrhizal fungi essential for the plant nutrient uptake. Furthermore, chemical leaching and accumulation lead to soil toxicity, reducing the fertility and increasing the susceptibility to erosion. Over time, this degradation not only jeopardizes the agricultural productivity but also destabilizes broader terrestrial ecosystems, posing long-term threats to environmental sustainability. Pesticides are typically applied as liquid sprays, granules, or seed treatments and can infiltrate the environment through various pathways, including leaching, volatilization, and surface runoff. Once introduced into the soil, pesticides can persist, disrupting critical biological processes. Soil microbes, which are essential for nutrient cycling, organic matter decomposition, and the overall soil fertility, are particularly vulnerable. Excessive pesticide use may irreversibly deplete these beneficial organisms, leading to soil degradation. Nitrogen-fixing microbes, essential for converting atmospheric nitrogen into bioavailable forms, are especially sensitive to certain fungicides and herbicides. For example, chlorothalonil and dinitrophenyl fungicides disrupt the nitrification and denitrification processes (Goswami et al., 2018), while triclopyr inhibits ammonia-oxidizing bacteria (Marileo et al., 2016; Pell et al., 1998). Glyphosate reduces the activity of nitrogen-fixing bacteria (Mohamed et al., 2021; Santos & Flores, 1995), and 2,4-D inhibits the microbial transformation of ammonia into nitrates (Ding et al., 2017; Frankenberger & Tabatabai, 1991). Herbicides also harm fungal communities, with trifluralin and oryzalin inhibiting mycorrhizal fungi that facilitate nutrient uptake. Oxadiazon reduces fungal spore populations (Sieverding & Leihner, 1984), while triclopyr exhibits toxicity toward specific mycorrhizal species (Chakravarty & Sidhu, 1987).

Earthworms, integral to soil health and fertility, are not exempt from pesticide-induced harm. These organisms, which serve as bioindicators of soil contamination, absorb pesticides primarily through soil pore water. Insecticides and fungicides induce neurotoxic effects and physiological damage in earthworms (He et al., 2021; Schreck et al., 2008). Glyphosate and chlorpyrifos inflict cellular-level damage, including DNA degradation, and adversely affect the feeding activity and viability (Mahmood et al., 2016). Neonicotinoids, which accumulate in soil, can lethally affect earthworm species such as *Eisenia fetida* and *E. andrei* (Chevillat et al., 2017).

In summary, the pervasive overuse of agrochemicals has inflicted profound ecological damage, disrupting aquatic and terrestrial ecosystems, degrading soil health, and contaminating water resources. The decimation of pollinator populations, avian species, soil microbes, and earthworms not only erodes biodiversity but also undermines vital ecosystem functions such as pollination, nutrient cycling, and soil fertility—services indispensable for sustainable agriculture and environmental stability. The widespread presence of agrochemical residues in surface and groundwater, coupled with the degradation of soil's biological integrity, signals an urgent need for transformative action. Addressing this multifaceted crisis demands the adoption of sustainable agricultural practices, including integrated pest management, and the establishment of rigorous regulatory frameworks.

17.6 Changing efficacy of agrochemicals in different climate scenarios

The application of agrochemicals, particularly chemical fertilizers, plays a pivotal role in driving climate change (Intergovernmental Panel on Climate Change (IPCC), 2023). Among these, synthetic nitrogen fertilizers are the most significant contributors to agricultural GHG emissions due to the release of nitrous oxide (N_2O), a potent GHG. The Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2023) has reported that the agricultural sector is responsible for approximately 24% of global GHG emissions (FAO, 2013). Additionally, the use of pesticides and fertilizers has far-reaching impacts on ecological balance, environmental health, and human well-being. An excessive application of heavy metal-based agrochemicals has been linked to soil degradation, notably through elevated nitrate and sulfate concentrations, which subsequently impair groundwater quality (Gupta et al., 2021; Gupta, 2022; Kumar et al., 2024).

Climate change is projected to alter the dynamics of pathogen prevalence and chemical behavior in the environment, influencing their exposure, transport, and fate. Such changes could exacerbate disease and pest pressures, thereby necessitating greater reliance on agrochemical inputs. While pesticides contribute to agricultural productivity, their overuse poses significant ecological and health risks. Overreliance on pesticides has been associated with the decline of beneficial organisms, including birds, natural predators like *Chrysoperla carnea*, ladybird beetles, spiders, parasitoids like *Apanteles* spp. and *Trichogramma* spp., as well as pollinators and soil fauna such as earthworms (Houghton, 2000).

An indirect yet notable consequence of climate change is the potential emergence of late-season agricultural pests. These pests, which typically become economically significant during mid-summer, may necessitate additional pesticide applications to prevent crop losses (Koli et al., 2019). Such shifts underscore the complex interplay between climate change, pest dynamics, and agrochemical use, emphasizing the need for sustainable agricultural practices to mitigate environmental and ecological harm.

Elevated temperatures associated with climate change may necessitate early pesticide applications in summer, thereby increasing the environmental pesticide load. Koli et al. (2019) projected that climate change will enable certain pests to survive through winter and promote the accelerated development of summer-active species. Consequently, this may drive an increase in pesticide use, which could amplify adverse environmental impacts. However, comprehensive information on the interactions between climate change, pesticide use, and environmental outcomes remains limited.

Temperature and precipitation patterns, which are directly influenced by climate change, are expected to play a crucial role in the partitioning, transport, and fate of chemical toxicants (Henriksen et al., 2013). Koleva et al. (2009) demonstrated that climate variability significantly affects pesticide application rates in the United States, highlighting the influence of weather conditions on pesticide use. Similarly, Fahim et al. (2011) examined the impact of climate change on tomato diseases in Egypt, revealing that increased nighttime temperatures and prolonged winter seasons may contribute to higher disease incidence. Notably, the range of key diseases, such as

tomato late blight, has expanded since the early 1990s, a trend likely driven by climate change.

Shifts in climatic conditions are expected to influence pest and pathogen dynamics, pesticide degradation, and application efficacy. For instance, higher temperatures may accelerate pesticide degradation, increased precipitation could promote chemical runoff, and reduced moisture availability in arid conditions may limit the pesticide activity. These factors collectively point to the likelihood of increased pesticide usage for certain crops. Chemical pest control remains integral to global food production, as pests (including insects, pathogens, and weeds) account for the yield losses of approximately 17%–30% (Savary et al., 2019). The global use of chemical pesticides, primarily in agriculture, has risen by 600%—from around 0.5 Tg year⁻¹ in the 1950s to approximately 3.5 Tg year⁻¹ in 2021 (FAO, 2023). Despite this escalation, only a small fraction of applied pesticides reaches the target pests, while the majority is lost to the environment, posing significant risks to human health (especially among farm workers) and ecosystems (Pimentel & Levitan, 1986).

Climate change is poised to impact multiple dimensions of pest control, influencing pest pressure, pesticide application frequency, efficacy, persistence, and toxicity. These changes could further escalate pesticide usage, thereby heightening the ecological and human health risks associated with chemical pest control. Addressing these emerging challenges requires a deeper understanding of climate-driven shifts in pest populations and agrochemical dynamics, alongside the development of sustainable pest management strategies (Fig. 17.3).

Crop yields are influenced by various components of Earth's changing climate, including rising temperatures, altered precipitation and cloud patterns, elevated atmospheric CO₂ concentrations, and the increasing frequency of extreme climatic

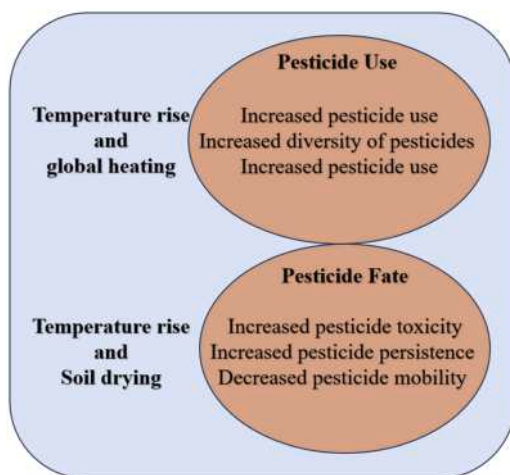


Figure 17.3 Variable effects of the impacts of climate change, in terms of increasing temperature and precipitation, on pesticide use and fate.

events such as heat waves, floods, and droughts (Kerr et al., 2022). The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Kikstra et al., 2022) concluded that climate change has predominantly exerted negative impacts on crop yields across most regions and food groups.

Temperature rise is a key driver of yield reduction, as higher temperatures accelerate the crop phenology, thereby shortening the crop growth cycle and intensifying water stress (Zhu et al., 2018). Zhao et al. reported that a 1°C increase in global temperature is associated with a 3%–7% reduction in the yields of major staple crops. While warming during cold seasons may alleviate cold stress for certain crops, it also poses the risk of insufficient chilling and vernalization—a critical process for flowering and fruiting in many temperate horticultural crops (Luedeling, 2012).

Livestock production is also adversely impacted by rising temperatures, leading to reduced feed intake, slower growth rates, and increased susceptibility to disease (Kerr et al., 2022). Aquatic food systems are not immune to climate-related impacts, as warming oceans and associated changes in marine environments are projected to reduce marine biomass. Lotze et al. (2019) estimated a 5% decline in marine biomass for every 1°C increase in ocean temperature, thereby posing significant risks to global fisheries and aquaculture systems.

Changes in precipitation patterns are reshaping the global agricultural landscape, with projections indicating an intensification of these impacts. Rainfall variability, particularly rainfall deficits and prolonged droughts, has historically undermined food production and supply stability. As climate change continues to exacerbate such extremes, the associated risks to global food security are expected to increase.

Between 1983 and 2009, approximately 75% of global croplands experienced significant yield reductions due to one or more drought events (Kim et al., 2019). The adverse impacts of extreme weather and crop failures were acutely felt in 2021 and 2022, when millions of people across 10 countries in Africa and Central America faced acute hunger or starvation (Oxfam, 2022). Even in highly industrialized nations, severe droughts have caused substantial declines in crop production, as observed in the United States in 2012 and Australia from 2001 to 2009 (Rippey, 2015; van Dijk et al., 2013). Furthermore, extreme rainfall and flood events have intensified localized food insecurity crises (Bhutta et al., 2022).

Long-term analyses suggest that climate change has already had a measurable impact on global agricultural productivity. Ortiz-Bobea et al. (2021) estimated that climate change-induced productivity losses over recent decades are equivalent to approximately seven years of technology-driven productivity growth. Elevated atmospheric CO₂ concentrations, as studied through 30 years of free-air CO₂ enrichment experiments, have yielded mixed outcomes for crop productivity. While C4 crops (e.g., maize, sorghum, millets) only exhibit productivity gains from increased CO₂ under drought conditions, C3 crops (e.g., rice, wheat, soybean, and most fruits and vegetables) generally experience yield improvements, especially in high-yielding cultivars (Ainsworth & Long, 2021). Given that about 75% of global cereal production is derived from C3 crops, this CO₂-driven productivity enhancement holds significant importance. However, the potential yield benefits of elevated

CO₂ could be partially or fully offset by the negative effects of droughts, which directly reduce productivity independent of temperature increases (Lesk et al., 2016).

Crop modeling studies predict that the combined impacts of climate change and rising CO₂ concentrations could reduce yields, particularly for maize in mid-latitude regions such as the United States, Midwest, Central Asia, and North China. Without changes to irrigation practices, these areas are projected to experience substantial yield losses (Jägermeyr et al., 2021; Rosenzweig et al., 2014).

Addressing the intertwined challenges of food security, climate change, population growth, and economic development requires a swift transition to more sustainable and climate-resilient food systems. This shift must prioritize the reduction of agriculture's environmental impacts while ensuring food security. Achieving this goal necessitates the large-scale adoption of sustainable practices and technologies that have already demonstrated efficacy in mitigating agriculture's environmental footprint. Overcoming socio-economic barriers to adoption is critical. Additionally, there is an urgent need for increased investment in agricultural research to develop novel production processes and alternative food products that are affordable, accessible, and appealing. Such investments would facilitate the transition to sustainable, climate-resilient, and healthier dietary systems.

17.7 Global policy and regulatory frameworks on agrochemicals

International norms and conventions serve as the primary regulatory framework for agrochemicals and serve as the basis for national regulatory policies. The World Health Organization (WHO) and the FAO collaborate to provide guidelines to protect the environment and public health. The FAO and WHO collaborated to create the International Code of Conduct on Pesticide Management, a crucial document that establishes voluntary guidelines for the use of pesticides in agriculture (FAO, 2018). Countries are also encouraged by the FAO's guidelines to create regulatory frameworks that incorporate risk evaluations, safe usage procedures, and the promotion of chemical pesticide substitutes. In order to guarantee that agrochemicals are safe for both consumers and the environment, the Organization for Economic Co-operation and Development (OECD) has created guidelines and instruments to support pesticide regulation on a larger scale. These include harmonizing the testing procedures, residue standards, and risk assessments (OECD, 2020). Despite providing crucial guidance, these international bodies lack the authority to enforce their recommendations; instead, national governments are responsible for putting them into effect through local laws and regulations.

17.8 National regulatory frameworks and policy development

National regulatory frameworks frequently mirror worldwide standards with extra particular criteria based on local conditions. They are intended to handle local

agricultural needs, public health issues, and environmental protection. One well-known example of a nation with extensive laws controlling the use of agrochemicals is the United States, through the Environmental Protection Agency (EPA). Prior to being marketed or used, all pesticides must be registered under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), which is administered by the EPA. The EPA can impose limitations or prohibitions on dangerous products after reviewing the efficacy, safety, and environmental impact of pesticides (U.S. EPA, 2020).

In a comparable manner, the European Union (EU) has implemented strict pesticide laws under Regulation (EC) No 1107/2009, guaranteeing that only pesticides that satisfy strict safety requirements for the environment and human health are permitted for use in EU member states. In order to protect consumers, member states have to implement maximum residue limits, that are limitations on pesticide residues in food.

The Insecticides Act of 1968, on the other hand, governs the use of agrochemicals in India through the Central Insecticides Board and Registration Committee. This law requires pesticides to be registered and guarantees that they adhere to strict safety and effectiveness requirements. But enforcement has frequently proven difficult, and there are worries about the agrochemical misuse, particularly in rural regions where farmers might not receive the necessary training on safe pesticide usage (Latt et al., 2023).

17.8.1 Challenges in agrochemical regulation

While many nations have extensive regulatory frameworks in place, there are still a number of obstacles to overcome in order to successfully manage the use of agrochemicals. Ineffective enforcement is one of the biggest obstacles. Lack of facilities technical know-how, and funding prevents agrochemical rules from getting properly implemented and monitored in many developing nations (Jha, 2021). This results in extensive abuse, including the excessive usage or the use of unapproved chemicals, which can pose major risks to human health and the environment. The effect of politics and the economy on the regulatory process presents another difficulty. Despite safety concerns, political pressures in some areas may result in the acceptance of agrochemicals (Scholz et al., 2022). For instance, agrochemical companies or the financial pressures of raising agricultural productivity to satisfy food demands may speed up the approval procedure for specific chemicals in developing nations.

Risks to the environment and human health present serious difficulties as well. Overuse of agrochemicals can pollute natural habitats and damage biodiversity by contaminating the air, water, and soil. The decrease in pollinator populations, particularly bees, which are essential for crop pollination, has been connected to pesticides like neonicotinoids. Additionally, people residing close to treated fields and agricultural workers are at risk for pesticide exposure, which can result in a variety of acute and long-term health problems, including as cancer, neurological disorders, and respiratory difficulties.

17.8.2 Emerging risks and regulatory gaps

New regulatory issues arise with the introduction of new agrochemical products and technology, such as gene-edited crops and genetically modified organisms. For instance, current frameworks do not sufficiently handle the approval and control of gene-edited crops, which may call for novel insecticides or herbicides. In response to these technological developments, regulatory bodies need to create science-based assessment methods that into account new compounds long-term ecological and health effects in addition to their immediate effects.

Concerns have also been raised by the growing incidence of antimicrobial resistance brought on by the overuse of antibiotics in agriculture. This reveals a regulatory weakness in the control of veterinary medication use and its impact on human health. To solve this problem and balance the requirement for efficient pest and disease control in agriculture, new frameworks must be developed. (Singh et al., 2021).

17.8.3 Opportunities for improvement in agrochemical regulation

To address these challenges, several key actions can be taken to improve agrochemical regulation and make it more effective:

1. Increased monitoring and enforcement: Better national-level implementation of current laws, along with frequent inspections and monitoring, can prevent the abuse and guarantee the responsible use of agrochemicals. This endeavor will require more regulatory capacity, which includes more accessible testing tools and better-trained inspectors. (OECD, 2020).
2. Promotion of IPM: By integrating mechanical, cultural, and biological techniques with the sparing application of chemicals, IPM provides a more environmentally friendly method of pest control. IPM can be supported by governments through public awareness campaigns, farmer training programs, and policy incentives (FAO, 2018). IPM encourages ecologically friendly methods and lessens dependency on agrochemicals.
3. Public awareness and education: It is essential to inform farmers and the broader public about the safe application of agrochemicals as well as the dangers that excessive use poses to the environment and human health. National governments can create training programs to increase the knowledge and guarantee the safe handling and disposal of agrochemicals in partnership with international organizations such as the FAO and WHO (FAO, 2018).
4. Transparency and scientific rigor: Agrochemical approval procedures must be transparent and supported by solid scientific data, according to regulatory bodies. To guarantee that rules reflect the most recent scientific understanding and to harmonize risk assessment standards, more cooperation between governmental entities, international organizations, and independent scientists will be required (OECD, 2020).

Although agrochemicals are still essential to contemporary agriculture, their abuse and overuse present serious threats to biodiversity, the environment, and human health. To balance the advantages and disadvantages of agrochemicals, a strong legislative and regulatory framework is necessary. Although national laws and international standards offer a strong basis, issues like poor enforcement, political sway, and new threats underscore the necessity of ongoing development. A more safe

and sustainable use of agrochemicals can promote future environmental protection and agricultural productivity through increased international cooperation, more enforcement, increased use of IPM, and public education.

17.9 The future of agrochemicals in the context of climate change

Technological developments in pesticide formulations, the requirement for long-term sustainability, and the necessity to strike a balance between environmental preservation and agricultural productivity have all influenced this complicated and multi-dimensional issue. Although agrochemicals like pesticides, herbicides, and fertilizers have long been essential for increasing crop yields, their effects on the environment and human health have drawn criticism. Agrochemicals function is changing as a result of climate change, with new developments addressing efficiency and sustainability while preserving or improving food security.

Technological advancements in agrochemical formulations: Enhancing agrochemicals effectiveness, minimizing their negative effects on the environment, and increasing their application precision are all priorities in their development. The development of slow-release fertilizers and nanopesticides, which have drawn interest due to their more effective delivery of nutrients and pesticides, is one of the significant technological advances in this field. The problem of nitrogen loss, which is made worse by intense rains and altered precipitation patterns brought on by climate change, is addressed with slow-release fertilizers, which also decrease pollution and the nutrient runoff, maximizing the nutrient uptake by plants (He et al., 2021).

One significant advancement in agrochemical formulations has been nanotechnology. For instance, nanopesticides are made to act more precisely, minimizing the influence on nontarget species and using fewer broad-spectrum compounds (Rani et al., 2020). With farmers subject to more stringent environmental restrictions and public scrutiny about pesticide use, these technologies not only boost the efficiency of agrochemical use but also reduce their environmental impact. Furthermore, using naturally occurring organisms to manage pests and enhance soil health, biological fertilizers and insecticides are becoming more and more popular. These developments fit into the larger trend of IPM, which combines biological and chemical control techniques to lessen reliance on artificial pesticides (Zhao et al., 2017). This trend is particularly important as the agricultural sector is pressured to meet growing food demands in the face of diminishing natural resources and changing climates.

Long-term sustainability and the shift toward Green Chemistry: Reducing environmental degradation, improving soil health, and fostering biodiversity while preserving agricultural productivity are the key goals of long-term sustainability in agrochemicals. The overuse of synthetic pesticides and fertilizers is a major problem since it can damage beneficial creatures, degrade soil, and pollute water. The industry is shifting toward green chemistry, which stresses safer and more sustainable

formulations with lower toxicity to individuals and the environment, in order to address these issues (Fig. 17.4).

Another innovation that has promise for enhancing sustainability is the use of biodegradable chemicals. For instance, certain agrochemical chemicals are being developed to decompose more rapidly in the environment, which lowers the possibility of buildup in soil and water sources. Additionally, the idea of precision agriculture—which optimizes the timing and quantity of pesticide application using GPS, sensors, and data analytics—is crucial for reducing waste and raising the effectiveness of agrochemical use. By assisting farmers in using agrochemicals in a way that is both efficient and ecologically conscious, these technologies support the objectives of sustainable farming.

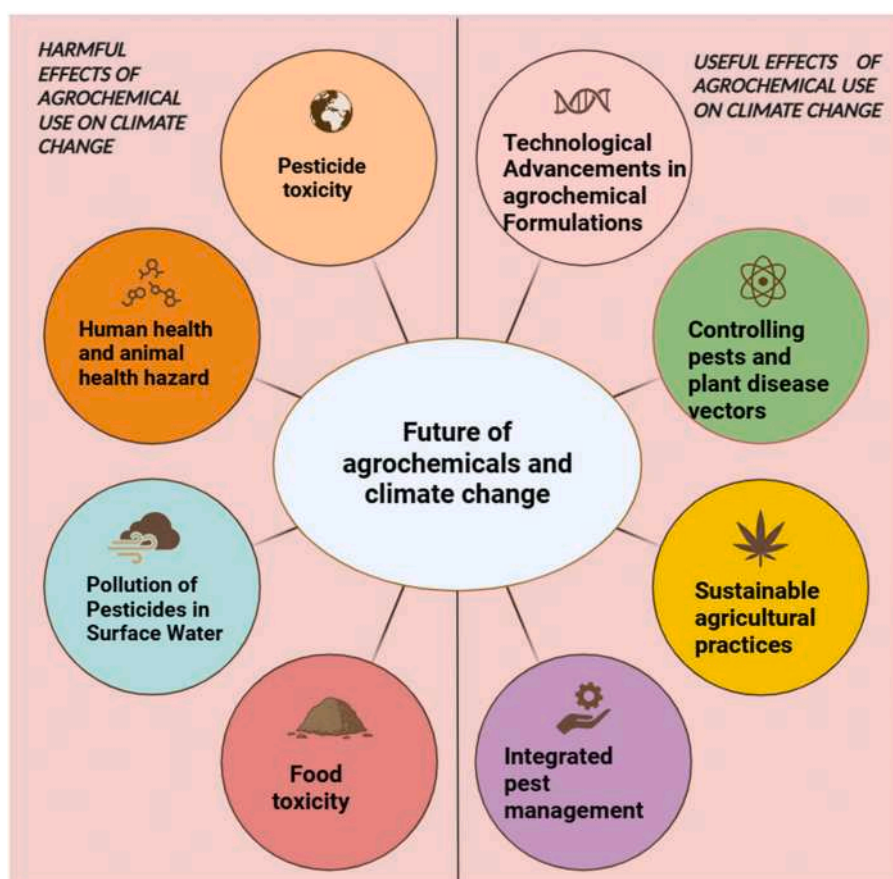


Figure 17.4 A figure illustrating the futuristic scope of agrochemicals in addressing the challenges and opportunities under changing climate scenarios.

With the world's population expected to reach about 10 billion people by 2050, agricultural output must rise to satisfy demand. Nevertheless, environmental deterioration cannot be the price of this. Therefore, the problem is to figure out how to strike a balance between the necessity of increasing yields and the need to lessen environmental consequences including soil erosion, greenhouse gas emissions, and biodiversity loss. In this delicate balancing act, agrochemicals will remain crucial, but their usage needs to be carefully controlled to prevent abuse and overuse. Regenerative agriculture is one strategy that has drawn interest; it blends the use of agrochemicals with techniques like crop rotation, cover crops, and decreased tillage that enhance the soil health and sequester carbon. These methods can lessen the requirement for synthetic inputs while increasing agricultural systems' resistance to climate change (Lorenz & Lal, 2022). In order to guarantee long-term productivity and environmental sustainability, agrochemicals can be utilized in combination with more ecologically friendly agricultural methods.

The creation of climate-resilient crops, which are bred or genetically modified to resist shifting climatic circumstances including drought, flooding, and increased insect pressures, is another promising tactic. Because they can handle stresses better without requiring excessive chemical interventions, these crops require fewer agrochemical inputs (Ray et al., 2020). In order to minimize the environmental impact of agricultural activities while responding to climate change, biotechnology integration with pesticide use may be essential. In light of climate change, the future of agrochemicals will rely on the ongoing advancement of technology that increase the products sustainability, accuracy, and efficiency. Technological developments like slow-release fertilizers, nanopesticides, and biological substitutes present encouraging answers to the problems with traditional agrochemicals effects on the environment and human health. These technologies must be used in tandem with more comprehensive agricultural policies that put sustainability first, like the creation of climate-resilient crops, precision agriculture, and regenerative techniques. To feed the world's population without endangering the ecological health of the earth, it is essential to strike a balance between the agricultural output and environmental stewardship.

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Smart crop varieties and Precision agriculture: a way ahead for climate-resilient sustainable agriculture

18

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18.1 Introduction

Climate change has emerged as a critical global challenge, profoundly influencing food security, human health, water resources, and societal development across the globe. Given that agriculture heavily depends on rainfall, temperature, and soil conditions, climate change disrupts this sector through irregular monsoons, droughts, and floods, leading to reduced crop yields and threatening farmers' livelihoods. For instance, a one-degree increase in mean temperature could reduce the productivity of various crops by 3%–7%, exacerbating the risks of hunger and malnutrition (Gregory et al., 2005). In India, small and marginal farmers, who constitute nearly 86% of the

farming population, are disproportionately affected by climate change compared to their larger counterparts. Unlike large-scale farmers, who are better equipped to adapt, small and marginal farmers face heightened vulnerability due to limited resources and adaptive capacities (Cohn et al., 2017). The repercussions of climate change extend beyond agriculture, significantly affecting labor productivity across various economic sectors highlighted that global warming could cause a 5.8% reduction in working hours, equating to the loss of approximately 34 million full-time jobs, with the construction and agricultural sectors being among the hardest hit. The challenges posed by climate change have been compounded by disruptions caused by the COVID-19 pandemic, which severely impacted the agricultural sector. Small-scale farmers were particularly vulnerable in regions with limited mechanization and inefficient procurement systems for farm produce (Dasgupta et al., 2021).

In India, the effects of climate change on agriculture vary by region. Predictions suggest an increase in extreme rainfall events in the western and south-central parts of the country, while summer monsoon rainfall may decline, and winter rainfall could rise in northwestern areas, including the arid regions of western Rajasthan and parts of Punjab and Haryana. These changing patterns are likely to cause more frequent droughts and floods, significantly affecting both *kharif* crops (sown between June and July and harvested between September and October) and *rabi* crops (planted between October and December and harvested from April to June). A study in the Brahmaputra basin revealed that farmers associate climate change with recurring floods, landslides, droughts, and an increase in crop and livestock diseases (Gupta & Pathak, 2016). The adverse impacts of climate change could potentially lead to a 4.5%–9% annual reduction in agricultural yields in India during the 2020–39 period. In monetary terms, this translates to an annual GDP loss of 0.7%–1.35%. However, these impacts can be significantly mitigated through robust climate change adaptation strategies, including sustainable agricultural practices, efficient water management, and the development of climate-resilient infrastructure (Babar & Amin, 2014). It refers to the adoption of adaptation, mitigation, and other techniques in agriculture that improve the system's ability to respond to diverse climate-related disturbances by preventing harm and recovering rapidly. It is agricultural system's capacity to recover from disturbances and disruptions caused by climate change. These disturbances include events like droughts, floods, heat or cold waves, irregular rainfall, extended dry periods, pest and insect outbreaks, and other threats linked to shifting climate patterns. Essentially, climate-resilient agriculture (CRA) is the system's ability to "bounce back" after such challenges. It incorporates an inherent ability to recognize threats requiring a response, along with the effectiveness of that response. CRA focuses on the wise and improved management of natural resources—such as land, water, soil, and genetic resources—by adopting optimal practices (Baraj et al., 2024) (Fig. 18.1).

Climate change and its variability have emerged as significant challenges for Indian agriculture, affecting its overall performance. Shifts in long-term weather patterns contribute to climate change, posing threats to agricultural productivity through fluctuations in temperature, increased unpredictability in rainfall, and rising sea levels. These changes risk the contamination of coastal freshwater sources and

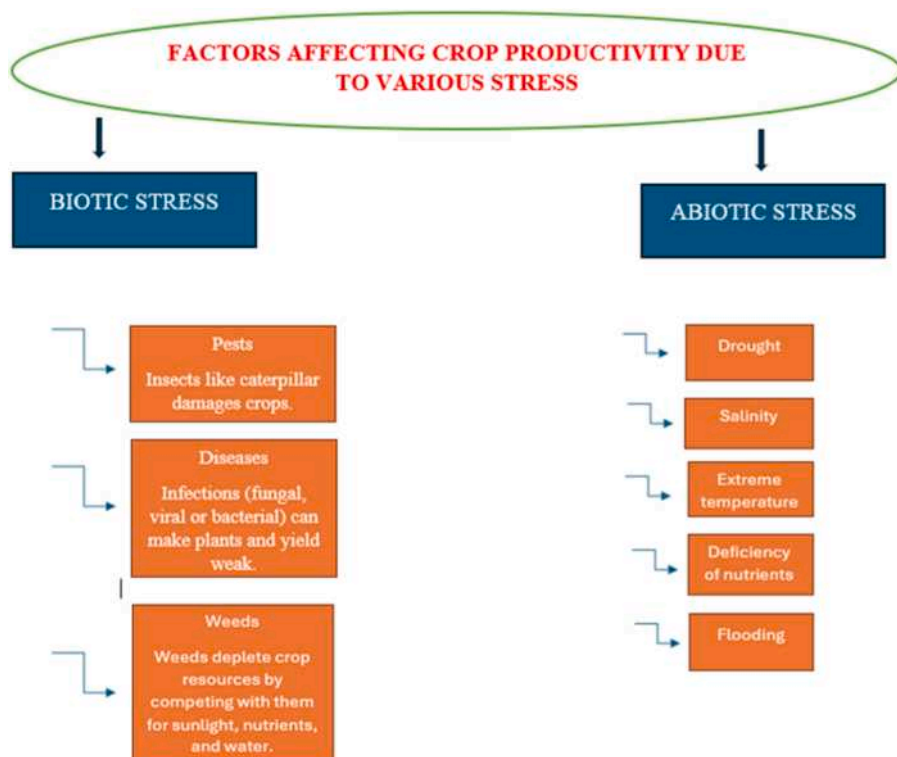


Figure 18.1 Factors affecting crop productivity due to various stress.

heighten the likelihood of flooding (Rao et al., 2016). The impacts of climate change, including global warming, touch all aspects of human life, but agriculture is particularly vulnerable. Higher temperatures often lead to lower yields in many crops and foster the spread of weeds and pests. While certain regions may experience yield increases or other localized benefits, the overall impact of climate change on agriculture is expected to be detrimental. Yields of irrigated crops will likely decline across regions due to higher temperatures and shifts in water availability. Rainfed agriculture, on the other hand, will be primarily affected by fluctuations in rainfall and a decrease in the number of rainy days (Aggarwal, 2008). Cyclones, frost, floods, hailstorms, droughts, and other climatic factors occur more frequently each year in one or the other part of the country. Changes in climate have affected all countries all over the world, the most affected being India, which has a high population where most people are reliant on agriculture and due to changes in climatic conditions, there is a shortage of naturally occurring resources with inadequate techniques (Elliott et al., 2014). Since there is a major decline occurring in production due to the reduction in the growth period, it might negatively affect grain filling and

reproduction, especially because of heat stress at the terminal stage and reduction in the water resource availability. Additionally, biodiversity would suffer, which will have an impact on agricultural output. The genetic variety is essential to the impoverished, particularly those residing in marginalized regions with low agricultural yield (Balasubramanian, 2018). A crucial prerequisite for sustainable development in the face of climate change is CRA, which includes adaptation and mitigation techniques as well as the efficient utilization of biodiversity at all levels, including genes, species, and ecosystems (Padulosi et al., 2013).

18.2 Framework of climate-resilient agriculture

The climate resilience framework emphasizes that the policy of climate change focuses on addressing unavoidable changes while preventing those which are beyond manageable limits. It begins with the idea of a climate resilience gap, which UCS describes as the degree to which people (individuals, communities, states, and even nations) are ill-prepared for the effects of climate change, leaving them vulnerable to potentially negative consequences. We must take active action on climate adaptation and mitigation to close the climate resilience gap and successfully respond to climate change. According to the Paris Agreement that was formulated on December 12, 2015, it was meant to keep the rise in the world average temperature to 1.5°C-over preindustrial levels and keeping it far below 2°C (Tyler & Moench, 2012; UNFCCC, 2015). Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (UNFCCC, 2015), almost all nations have agreed on a science-based goal of mitigating climate change (Teske & Pregger, 2022). Mitigation and adaptation strategies are closely related, and understanding this relationship is essential. In addition to reducing the long-term effects of climate change on future generations, stronger mitigation measures will increase the durability and value of today’s preparedness initiatives. We can be more confident that our preparations won’t be swiftly overtaken by a climate that is becoming more and more disruptive if we implement aggressive mitigation. Future adaption expenses can be decreased by making mitigation investments now (Laukkonen et al., 2009). Even if heat-trapping emissions were eliminated today, their atmospheric concentration would still be higher than it has ever been for many years. Generations will require adaptation measures to help close the resilience gap. As a society, we cannot afford to prepare for every scenario, so we can never completely close this gap because climate and weather have always included harsh and harmful situations. It is not feasible to prevent every natural calamity, both financially and physically, and the effects of climate change are no exception. Nonetheless, adaptation can help close the climate resilience gap, and climate impacts are a concern that is only becoming worse. To get ready for the anticipated effects of climate change, communities should take proactive measures (Ebi & Semenza, 2008). Even as sea levels rise, temperatures rise, and the climate becomes more erratic and unpredictable, they can effectively strengthen their climate resilience by, for instance, planting urban woods for shade

cover or restoring wetlands for flood management. The possible courses of action are numerous. Decision-makers can use the following adaption principles to help them focus their investments (Wang et al., 2024).

18.3 Principle of climate resilience

18.3.1 Sustainable agriculture

The concept of sustainable agriculture has gained popularity since the Brundtland Report was released in 1987. The concept of sustainable agriculture is highly imprecise and unclear, making its application and execution exceedingly challenging (Velten et al., 2015). To meet society's current food and textile demands without endangering the ability of present or future generations to meet their own, sustainable agriculture involves cultivating sustainable methods. It may be predicated on knowledge about ecological services. For sustainable agriculture development, there are several methods. While adopting sustainable agriculture in systems of food, it is crucial to develop procedures of business along with the techniques of farming that will be utilized. Agriculture has a huge environmental impact, contributing to climate change (one-third of anthropogenic greenhouse gas emissions come from food systems), water scarcity, water pollution, land degradation, deforestation, and other processes, and both causing and being affected by environmental changes (Brodt et al., 2011). The main negative impact of climate change is thought to be global warming, which is accompanied by other anomalies including the lack of water supplies, reduced agricultural output, food insecurity, rising sea levels, melting glaciers, and biodiversity loss. Climate anomalies have been linked to declining agricultural output and deteriorating water quality throughout time. On the productivity of crops, climate has a vital effect. It is impacted by annual climate fluctuations, shocks during various growth phases, extreme weather events, and long-term patterns in average rainfall and temperature (Srivastav et al., 2021). Most people agree that the most practical approach to feed expanding populations is through sustainable farming. Future costs to the environment and the communities they support must be taken into account in farming operations if the world's population is to be properly fed. For the purpose of the industry that is sustainable, the use of technology declined due to a decrease in resources. The ability to feed the world's expanding population is the ideal outcome of this development. The widespread concern that the planet's carrying capacity is also known as the planetary boundaries that have been reached or even beyond in terms of its capability to feed people that are in favor of sustainable agriculture (Tisdell, 2014).

In agriculture, sustainability is linked to several fundamental ideas. The integration of ecological and biological processes into agricultural and food production methods, such as nitrogen fixation, soil regeneration, and nutrient cycling—reducing the use of unsustainable and nonrenewable inputs, particularly those that harm the environment, utilizing farmers' knowledge to cultivate the land in a profitable manner, and encouraging farmers' independence and self-sufficiency—resolving issues related to agriculture and natural resources by bringing together individuals with diverse

backgrounds. Among the issues addressed are irrigation and pest control (Verma et al., 2019). Excessive tilling of the soil that causes erosion and irrigation without proper drainage that causes salinization are two practices that can harm soil over time. Climate, soil, nutrients, and water supplies are the most crucial elements for a farming location. The two that can be changed by humans—the most out of the four are soil and water conservation. Farmers take certain nutrients out of the soil when they plant and harvest crops. Without replenishment, the land experiences nutrient depletion, which results in decreased yields or the land being useless. Restoring the soil while reducing the consumption or requirement of nonrenewable resources, like mineral ores or natural gas, is essential to sustainable agriculture. Sustainable agriculture is not practiced by a farm that can “produce perpetually” but has detrimental consequences on the environment elsewhere (Mohanavelu et al., 2021). Financial obstacles prevent many smallholder farmers, especially those in emerging nations, from acquiring the tools and techniques that would increase their resilience. These challenges can be addressed with the aid of financial assistance in the form of grants, subsidies, and microfinance. A key component of climate-resilient agricultural systems is sustainable agriculture. It entails a comprehensive strategy that combines economic, social, and environmental aspects to create farming systems that are productive, adaptable, and ecologically conscious (Abiha et al., 2021). As climate change continues to threaten food security, innovative and scalable climate-resilient strategies are increasingly essential (Robinson, 2018). Genetically modified crops, heat-resistant varieties, and drought-tolerant plants are valuable tools for adapting to changing climatic conditions. Similarly, ensuring livestock breeds that can withstand heat stress, diseases, and drought is crucial for maintaining productivity during extreme weather events. Developing climate-resilient infrastructure, such as water storage systems, flood defenses, and climate-smart irrigation technologies, can help protect farms from the adverse impacts of floods and droughts. Additionally, rural infrastructure, including roads and storage facilities, must be designed to endure the effects of climate change (Havemann, 2013). However, financial challenges hinder the adoption of sustainable agricultural practices, including low financial returns, limited incentives, and insufficient capital investments. Economic factors significantly influence the implementation of sustainable farming techniques. Transitioning to sustainable agriculture requires both human and material resources, including staff training and significant investments in new technologies and products (Chaudhary et al., 2020).

18.3.2 Diversified farming systems and mixed farming

Small-scale, diverse farming systems that rely heavily on local resources and complex crop arrangements provide stable and efficient agricultural models, yielding a high return on an investment relative to labor and energy input. Small-scale tropical farmers frequently implement complex polycultures and agroforestry systems that mimic natural ecosystems in both structure and function. These systems share key traits with natural communities, such as layered vegetation, efficient nutrient recycling, resilience to pest infestations, and rich biodiversity (Altieri & Nicholls, 2004).

Diversified farming systems (DFS) involve a range of methods and tools that leverage natural diversity across plots, fields, and landscapes to support sustainable food production. These systems are adapted to local conditions and incorporate a variety of cultural traditions, practices, and governance structures worldwide. By creating an intricate network of natural and human ecologies, DFS helps sustain and restore essential ecosystem services, such as pollination and pest regulation, within agricultural systems. Human knowledge is fundamental in preserving these ecological functions (Kremen et al., 2012)

While DFS do not follow a single blueprint, they all prioritize local production, agroecological practices, and holistic approaches that enhance natural diversity and ecosystem services from the field to the broader landscape (Kaplan, 2021). By implementing agroecological techniques and diversified farming models, smallholder livelihoods can be improved, poverty can be reduced, and food insecurity can be addressed in both rural and urban areas.

Diversified agriculture is indispensable for feeding the global population sustainably, mitigating climate change, and safeguarding the ecological systems essential for human survival. Climate change-induced shifts in rainfall patterns and temperature introduce new challenges for industrial agriculture, as unpredictable weather leads to inconsistent harvests. As a research hub at UC Berkeley, the DFS Center focuses on advancing secure, resilient, and socially equitable global food systems through systems-based agriculture (Altieri et al., 2015). The Earth's finite natural resources are increasingly strained due to current patterns of population growth and consumption. Agriculture, as it is currently practiced, faces significant threats from the complex interactions between climate change and the depletion of resources such as land, water, oil, and fertilizers. Ironically, large-scale industrial monoculture agriculture exacerbates its own challenges by degrading soils, polluting waterways, creating oceanic dead zones, eliminating biodiverse habitats, and accelerating global warming (Ehrlich et al., 1993). Concerns about "feeding the world" often arise from predictions that global food demand will double by 2050. However, these calculations typically assume that current trends in population growth, consumption patterns (such as increasing demand for meat and luxury goods), and food waste will remain unchanged. Addressing these challenges requires transformative shifts in agricultural practices, dietary habits, and resource management to ensure a sustainable and equitable food future (Baggini, 2024).

In agriculture, mixed farming is a farming strategy that entails raising livestock and crops on the same plot of land for a specific season. This agricultural method, which is used all over the world, contributes to sustainable agriculture. The crops and animals work together in mixed farming, with the crops giving the animals food and fodder and the animals adding manure to the soil and occasionally using their labor in the fields. This integration makes farming a popular and useful practice by assisting farmers in diversifying their revenue streams, lowering risks, and making effective use of resources. Farmers have come up with creative ways to make their farms profitable. They have been able to raise cattle and crops at the same time by making the most of their available space (Altieri, 1981). The mixed diversity and mixed agricultural systems are better equipped to adjust to shifting market needs and

climatic fluctuations. While maintaining traditional farming methods, mixed farming can support farmers' livelihoods and promote food security and rural development (Lin, 2011). By enhancing ecological stability, maximizing resource usage, and lowering vulnerability to climatic extremes, mixed farming and DFS are essential components of CRA. To mitigate the consequences of erratic weather patterns, like droughts or floods, DFS incorporates a range of crops, livestock, agroforestry, and other activities. This helps disperse risks and guarantee a more steady income. By using crop rotation, manure, and organic matter inputs, mixed farming—which mixes the production of crops with livestock—improves soil fertility, improves soil health, and retains moisture, hence reducing soil degradation. Because different crops have different water requirements and animals can act as a backup in the event of crop failure, this diversification also promotes better water management (Dharmasena, 2024). These systems improve ecosystem resilience, decrease the prevalence of pests and diseases, and lessen reliance on chemical pesticides by fostering biodiversity. Diversified and mixed systems not only improve the environment but also promote economic stability by lowering dependency on a single crop, guaranteeing steady supplies of food and revenue, and promoting carbon sequestration. These farming practices facilitate both climate change adaptation and damage mitigation, making them essential tactics for climate-resilient, sustainable agriculture (Salisu et al., 2024).

18.4 Impact of changing rainfall patterns and drought

Change in climate is becoming more widely acknowledged that changing weather patterns are mostly caused by climate change, which has important ramifications for agricultural systems around the world. Changes in rainfall patterns and the frequency and severity of droughts are two of the most prominent examples of these changes. These changes pose serious threats to food security, agricultural productivity, and the farming community's livelihoods because agricultural systems are heavily reliant on climate variables, especially in areas that are already at risk from extreme weather (Samuel et al., 2021). Rainfall has a significant impact on soil moisture, crop growth, and overall agricultural production. Climate change has a direct impact on food production systems by changing the distribution, timing, and intensity of rainfall. Climate change has changed seasonal rainfall patterns in many places, causing longer dry spells in some places and more powerful and erratic rainfall events in others. Farmers find it challenging to forecast when to sow and harvest crops because of this change, which also throws off traditional cropping cycles. For example, severe rainfall events can result in waterlogging, soil erosion, and crop loss, while early-season droughts or delayed rains can cause planting failures. These disturbances make farmers more susceptible to crop failure and food insecurity in regions where rainfed agriculture is the predominant practice (Prasad et al., 2014) (Fig. 18.2).

Variability in average rainfall has increased, and extreme weather events like floods, dry spells, and torrential downpours are occurring more frequently. Farmers find it more difficult to control risks and make plans for the best possible agricultural

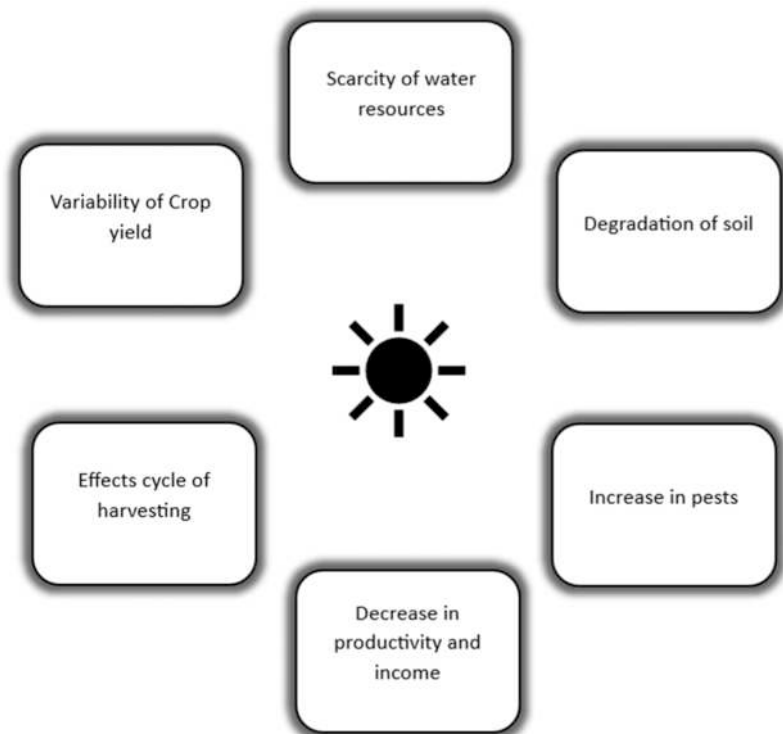


Figure 18.2 Impact of changing rainfall patterns and drought.

output in an environment that is uncertain due to this variability. While extended dry spells or irregular rainfall can cause water stress, which lowers crop yields and increases the requirement for irrigation, floods can wash away seeds and destroy standing crops (Sarma et al., 2024). One of the most significant effects of shifting climatic patterns on agriculture is drought. Long-term water shortages deplete soil moisture, which is critical for plant development. Droughts led to long-term soil damage, decreased crop yield, and worse water shortages (Chikodzi, 2016). Crop yields are directly decreased by droughts, especially for crops that require a lot of water, such as wheat, rice, and maize. Farmers are likely to have reduced agricultural production in drought-prone areas, which lowers the supply of local food and raises food prices. Food insecurity can be brought on by ongoing drought, especially in areas with a high prevalence of subsistence farming and poor irrigation systems (Chikodzi, 2016). Degradation of the soil can also result from prolonged drought, especially through processes like soil erosion and desertification. The structure of the soil deteriorates with decreasing soil moisture content (MC), increasing its

vulnerability to erosion by wind and water. Furthermore, there is less groundwater recharge due to decreased rainfall, which makes it more challenging to maintain sustainable irrigation techniques. A negative spiral in agricultural productivity and farmer livelihoods is a result of this cycle of drought, soil erosion, and water stress (Banga & Kang, 2014). A variety of adaptation measures have been developed by farmers, policymakers, and researchers to lessen the effects of drought and shifting rainfall patterns. In the face of future climate uncertainty, these tactics seek to guarantee food security and strengthen agricultural systems' resistance to climatic variability. In areas with unpredictable rainfall patterns and water scarcity, effective water management techniques are crucial. Water utilization can be maximized by employing strategies like drip irrigation, rainwater collection, and drought-tolerant cropping. There is a lot of potential for improving resilience through the creation of drought-resistant crop varieties via breeding initiatives or biotechnological advancements.

These innovations contribute to a more dependable agricultural water supply and less reliance on erratic rainfall (Dagar & Yadav, 2017). The integrated strategy known as climate-smart agriculture (CSA) seeks to lower greenhouse gas emissions, boost climate change resistance, and raise agricultural productivity. Soil conservation methods, including crop rotation, mulching, agroforestry, and the application of organic fertilizers, are examples of CSA practices. These methods maximize land use, boost biodiversity, and increase soil structure and moisture retention. CSA promotes the use of climate information services, which help farmers better predict weather trends and modify their operations accordingly (Hussain et al., 2022). One important tactic for increasing agricultural systems' resilience is diversification. Farmers can disperse risk and lessen their reliance on a single crop by diversifying their farming operations, livestock, and crops. This method can lessen the likelihood that crops will fail because of drought or unpredictable rainfall. Additionally, combining crops and cattle can increase farm revenue and offer more dietary options, which will increase resilience even more (Chary et al., 2022). Promoting CRA is a major responsibility of governments and international organizations. Building long-term resilience requires policies that encourage the adoption of climate-smart practices, make investments in water management infrastructure, and give farmers financial assistance. Initiatives to increase capacity, such as courses on climate adaptation for farmers, are also essential to guarantee that information is shared efficiently (Marke, 2014). Drought and shifting rainfall patterns have a significant impact on agriculture, influencing crop yields, food security, and farmers' livelihoods, especially in areas that are already at risk. The necessity for immediate action to improve the resilience of agricultural systems is highlighted by the increasing frequency and severity of extreme weather events. Farmers can increase their ability to adapt and lessen their susceptibility to climate unpredictability by implementing creative water management techniques, crop diversity, CSA, and early warning systems. To achieve long-term success, governments, businesses, and international organizations must work together to support laws, infrastructure, and capacity building that promote climate-resilient, sustainable farming methods (Trenberth, 2005).

18.5 Technological Innovations

18.5.1 *Smart-crop varieties*

To sustain and enhance agricultural yields while addressing the challenges posed by climate change, it is crucial to develop and identify climate-resilient crop varieties with improved tolerance to drought, flooding, heat, and salinity stresses. Enhancing the farming community's productivity and profitability while minimizing agricultural risks is essential to improving the livelihoods of millions dependent on agriculture. Abiotic stressors such as drought, heat, or cold trigger various plant responses, including changes in signal transduction pathways, gene expression, metabolic processes, and molecular mechanisms. These responses ultimately influence growth and adaptation through modifications in source-sink relationships, underscoring the necessity to identify key traits that contribute to stress tolerance (Murungweni et al., 2016). Abiotic stress tolerance in plants refers to their ability to efficiently utilize limited resources during stressful conditions and regain high productivity once the stress is alleviated.

In a number of crops, the regulation of genes for stress tolerance and resource-use efficiency is ruled by multiple loci which are distributed across the genome, making it a quantitatively controlled trait (Dwivedi et al., 2020). Gaining insights into the genetic correlation between these traits is essential for developing climate-resilient crop varieties and improving agricultural productivity. Numerous crop improvement programs prioritize enhancing yield potential while ensuring resilience to various abiotic stresses such as heat, salinity, drought, and flooding. To achieve sustainable food production and meet the rising global demand, farmers need access to climate-resilient crops alongside a steady supply of high-quality seeds. These varieties must not only maintain stable yields under stress conditions but also demonstrate high productivity in optimal environments. The application of advanced breeding strategies and biotechnological innovations will play a key role in overcoming these challenges and ensuring global food security (Umesh et al., 2019).

18.5.1.1 *Drought-resistant crop varieties*

The plants that are especially bred are known as drought-resistant varieties of crops that can sustain extended periods of scarcity of water without affecting growth or the result. Areas that are more affected by drought due to climate change, these varieties are essential for the maintenance of food security. Scientific research indicates that a crop's drought tolerance arises from a combination of physiological, biochemical, and genetic traits that enable it to survive and perform well under water-limited conditions (Blum, 2010). Drought-resistant crops employ various strategies to minimize water loss, one of the most important being their ability to reduce transpiration. By closing their stomata—tiny pores on leaves responsible for gas exchange—they effectively limit water loss to the atmosphere.

This aids in the plant's water conservation. To obtain water from deeper soil layers, these crops frequently grow larger or deeper root systems. This ensures that even in situations where surface moisture is very low, the plant can continue to take water.

Crops that can withstand drought may develop thicker, smaller, or waxy-coated leaves, all of which help to prevent water loss. To reduce their exposure to the sun during the warmest times of the day, several crops also change the orientation or angle of their leaves. Certain solutes, including proline, sugars, and other osmotic regulators, are frequently accumulated inside the cells of drought-tolerant plants. By stabilizing proteins and enzymes and lessening the effects of dehydration, these substances support cellular activity (Lynch, 2013).

Plant cells may sustain damage because of reactive oxygen species (ROS) produced during drought stress. To combat this, crops that can withstand drought frequently develop more antioxidants, such as catalase and superoxide dismutase (SOD), which lessen oxidative damage. Certain plants can withstand extended drought by developing specific vacuoles or having specialized cells that can store water (Impa et al., 2012). Selective breeding has historically been used to create drought-resistant crops, selecting plants that naturally withstand drought to create offspring that are more resilient to drought. Although it may take several generations, this technique has produced variants with higher water-use efficiency. The development of crops resistant to drought has been accelerated by contemporary methods such as genetic modification (GM) and gene editing (e.g., CRISPR). To introduce particular genes that give drought tolerance, scientists can directly alter the plant's DNA. To increase a plant's tolerance for dry circumstances, for instance, genes that control osmotic adjustment or stomatal closure can be added (Rosero et al., 2020).

Researchers have been able to discover genes and proteins linked to drought tolerance because of advancements in genomics. Researchers can better understand the molecular mechanisms involved and apply this knowledge to improve drought tolerance in crops by examining the gene expression, that is, transcriptomics and protein production, that is, proteomics of plants under drought stress. More biomass or yield can be produced per unit of water by drought-resistant crops since they frequently have higher water-use efficiency. This is accomplished by limiting water loss and optimizing processes such as photosynthesis. For crops to flourish in water-limited conditions, water usage effectively (WUE) is a crucial characteristic (Gosal et al., 2009). Advanced genetic methods, biochemical processes, and natural physiological adaptations are all used to create crop varieties that are resistant to drought. To ensure food security in the face of growing water shortages and climate change, scientists are attempting to develop crops that can flourish in water-limited regions by improving these features (Bashir et al., 2021; Shruti et al., 2023).

18.5.1.2 Heat-tolerant crop varieties

Crops that have been engineered to tolerate or even flourish in high temperatures are known as heat-tolerant crop varieties. Heat tolerance is for guaranteeing food security as global temperatures rise because of climate change. Reduced yields can result from heat stress' effects on a number of physiological and biochemical processes in crops. To maintain productivity in challenging environments, heat-tolerant cultivars are developed to mitigate or adapt to these stresses (Albahri et al., 2023). Elevated transpiration due to high temperatures can lead to excessive water loss. However,

heat-resistant plants possess enhanced control over their stomatal activity—tiny leaf pores—reducing water loss and decreasing the risk of dehydration. Additionally, a group of proteins called heat shock proteins (HSPs) plays a crucial role in helping plants endure heat stress.

Higher amounts of HSPs, which act as molecular chaperones to stop other proteins from denaturing (unfolding) under heat stress, are produced by heat-tolerant crops. HSPs enable the plant to preserve cellular function by repairing or refolding broken proteins (Ben-Yehoshua & Rodov, 2002).

Enzymes, especially those involved in carbon fixation such as RuBisCO in C3 plants or the enzymes in C4 plants, may be present in heat-tolerant crops and continue to function under heat stress. Despite disturbances brought on by heat, this helps sustain output. Compared to C3 plants, crops that use the C4 or crassulacean acid metabolism pathways are typically more heat tolerant. C4 plants, like sorghum and maize, can fix carbon more effectively in hotter climates by reducing photorespiration, a wasteful process that intensifies in hotter climates. Several crop types have undergone genetic modification or breeding to withstand heat, for example, rice, wheat, and corn. During flowering, rice is extremely vulnerable to heat stress. To increase production in tropical and subtropical areas, scientists have created heat-tolerant rice varieties that can withstand greater temperatures throughout the flowering season. Wheat is another crop that suffers from heat stress, especially during grain filling. In areas where temperatures are rising, it is crucial to breed wheat types that can withstand the heat to guarantee consistent yields. Breeding efforts to increase heat tolerance have focused on maize, which is especially susceptible to heat during the pollination phase. Some cultivars have been created to withstand elevated temperatures while maintaining sustainable yields (Kumar et al., 2023).

18.5.1.3 *Flood-resistant and waterlogging-tolerant crops*

Crops that can withstand flooding and waterlogging are specifically developed or engineered to flourish in conditions where an abundance of water, whether from floods or extended waterlogging, lowers soil aeration and interferes with plants' ability to grow normally. Through breeding and biotechnology, some crops have evolved or been designed to tolerate situations that would ordinarily result in considerable crop loss, such as prolonged soil saturation, harm from submerged conditions, or limited oxygen supply in the root zone (Daniel & Hartman, 2024). Crops that can withstand flooding and waterlogging have developed or been genetically modified to activate genes in response to hypoxic i.e. low oxygen environments. Anaerobic pathway activation takes place when plants can generate energy without oxygen by using genes that control anaerobic respiration-related enzymes including pyruvate decarboxylase and alcohol dehydrogenase. Handling oxidative stress also occurs where; ROS, which can harm plant cells, are frequently produced as a result of stress brought on by waterlogging. By producing more enzymes like catalase and SOD, which lessen oxidative damage, tolerant crops strengthen their antioxidant defenses (Agarwal & Grover, 2006). One of the best-known crops that can withstand flooding is rice. Some rice types, like those with the

SUB1 gene, have been bred for increased submergence tolerance since rice is frequently farmed in flooded fields, or paddies. By controlling anaerobic stress, reducing development, and preserving energy, these types can endure submerged conditions for up to two weeks. Some wheat varieties are being produced with enhanced tolerance to waterlogged soils, however in general, wheat is less resistant to floods than rice. These cultivars are frequently cultivated for improved root systems and the capacity to tolerate root zone oxygen deprivation. Crops like taro and cassava that are tropical crops have adapted to withstand damp, humid circumstances. These crops can endure for long periods of time in wet soils and frequently have specialized root systems (Carriere, 2000). Crops that can resist floods and waterlogging are crucial for reducing the effects of climate change, especially in areas that experience frequent or protracted flooding. These crops have several physiological, biochemical, and genetic adaptations that let them grow despite water stress, lessen cellular damage, and adapt to low oxygen levels. To ensure food supply in flood-prone areas, scientists are creating crops that are more resilient to flooding and waterlogging through both conventional breeding and cutting-edge genetic engineering (Rupngam & Messiga, 2024).

18.5.1.4 *Pest and diseaseresistant varieties*

Types of genetic resistance which interacts with the pathogen or pest and prevents from establishing successful infection or damage can be divided into two types: Vertical resistance and Horizontal resistance. Vertical resistance is a resistance that is race- or biotype-specific for a particular pathogen. It is usually controlled by one or a few genes and provides very effective resistance to certain strains. However, its longevity is limited as pathogens can easily evolve to outsmart it. Horizontal resistance: commonly known as general resistance, it is the one providing greater resistance to a range of pathogen races or biotypes. Generally controlled by more than one gene and thus more durable, forms of resistance. Nonhost resistance and apparent resistance: In this category are those characteristics of plants that simply inhibit or restrict infection or damage from a pathogen without any apparent contact or interaction with the latter. Nonhost resistance: In this type of resistance, plants are somehow lacking in the required receptor or compatibility factors needed to be infected by the pathogens. Such resistance is often strongly durable and broad-spectrum. Apparent resistance: when plants show traits that can make them less available and attractive to pathogens, such as structural architecture, leaf morphology, or merely the presence of some forms of physical barriers, a phenomenon called apparent resistance manifests. Plant defense mechanism: plants have a highly complex network of defense mechanisms that can be activated upon pathogen attack. They can be broadly categorized into preinfectious and postinfectious defenses. The physical and chemical barriers that prevent pathogen entry or inhibit growth called preinfectious defenses. These include morphological and structural features such as waxy cuticles, trichomes, and stomata, besides biochemical defenses like antimicrobial compounds and enzymes. Activated after infection and encompass a variety of responses which limit the growth and proliferation of pathogens are the

postinfectious defenses. They encompass the production of antimicrobial compounds, the hypersensitive response, which is an inducible cell death localized to the infected sites, and systemic acquired resistance as a whole plant defense. Disease escape and tolerance: these are not really resistance mechanisms but strategies that can reduce crop loss caused by pathogens. It means planting crops at times or locations where disease pressure is low, or through early-maturing varieties that escape infection before the population of the pathogen builds up. Plants tolerant to some degree of infection may survive at least with little yield loss. This may be through mechanisms that enable the plant to compensate for the damage done by the pathogen (Fig. 18.3).

Pest- and disease-resistant crop types are plants that have been specifically created or genetically altered to resist or endure attacks by pests (insects, mites, and nematodes) and diseases (bacteria, fungus, viruses, etc.). Because they can minimize crop losses, increase food security, and drastically reduce the use of chemical pesticides, these cultivars are essential for sustainable agriculture. According to science, pest and disease resistance is the result of a complex interaction between genetic characteristics, plant defense mechanisms, and biotechnological advancements that enable plants to detect, react to, and repel harmful organism attacks (Singh & Singh, 2005). When a pathogen attacks a plant, it frequently triggers SAR, a defense mechanism that includes the synthesis of signaling chemicals such as salicylic acid. Even in tissues that are not currently diseased, this tells the entire plant to strengthen its defenses against future illnesses. The plant is resistant to pests and

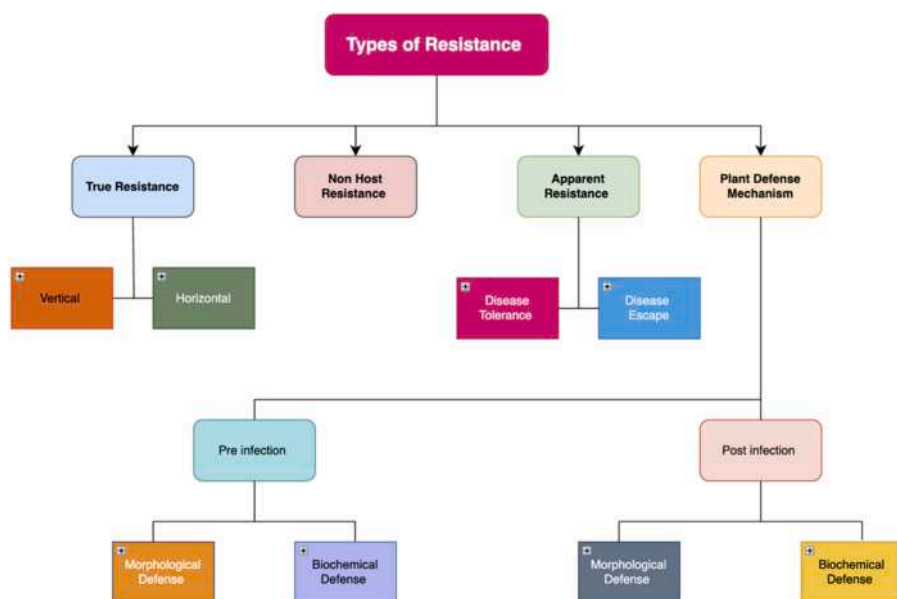


Figure 18.3 Various types of resistance are seen in plants.

illnesses due to its innate genetic characteristics. This entails triggering the plant's defense mechanisms, which can include biochemical reactions and physical barriers. Tolerant varieties: these cultivars are resistant to disease or insect attacks without experiencing appreciable yield reductions. Although they may not be able to totally fend off the pest, plants that are tolerant can endure the attack and still yield a respectable crop.

Some plants can resist infection or infestation right away because of their high immunity. This includes intricate defenses that are frequently activated when infections or insect invasions are detected (Tripathi et al., 2019). By adding genes that give pest and disease resistance, modern biotechnology technologies have made it possible to generate resistant crops more precisely and quickly. *Bacillus thuringiensis* (Bt) toxin is expressed in Bt cotton and Bt corn, two of the most well-known genetically modified crops. While this toxin is safe for people and animals, it is toxic to some insect pests, such as cotton bollworm and the European corn borer. Crops, including papaya, have undergone genetic modification to make them resistant to viral infections like the papaya ringspot virus. By introducing resistance genes, rice and wheat types have been modified to withstand fungal diseases such as wheat rust and rice blast (Sharma et al., 2004). Rice is extremely susceptible to several pests and diseases, including bacterial blight, rice blast, and rice weevils and leafhoppers. Varieties resistant to bacterial blight produced by *Xanthomonas oryzae* and rice blast caused by the fungus *Magnaporthe oryzae* have been created through breeding and genetic engineering. The Pi54 gene resists rice blights, whereas the Xa21 gene confers resistance to bacterial blight. Cotton has been genetically modified to withstand a significant pest, the bollworm. By producing a protein that is harmful to bollworm larvae, the Bt gene reduces the need for chemical pesticides and safeguards the crop. Diseases like late blight, which is brought on by *Phytophthora infestans*, can affect potatoes. NewLeaf potatoes, which produce a protein from *B. thuringiensis* to withstand insect infestations and specific blight strains, are one example of the disease-resistant variety created by genetic engineering (Paul et al., 2022). Plant defenses, such as chemical insecticides and genetically modified features, can cause pests to become resistant over time. Some insect populations, for instance, have developed resistance to Bt poisons. Integrated pest management (IPM) solutions are being developed to combat this by combining sustainable pesticide use, biological control, and resistant crops. Resistance to one strain of a pathogen does not necessarily translate to resistance to all variants since pathogens can change quickly.

Advancements in gene editing, particularly the CRISPR-Cas9 technique, have enabled precise modifications to plant genomes. Scientists can insert, delete, or modify specific genes that confer resistance to pests and diseases. Using CRISPR, researchers can develop crops with enhanced disease resistance, such as potatoes resistant to late blight or tomatoes resistant to gray mold (Umesha et al., 2018). Pest- and disease-resistant crop varieties play a crucial role in boosting yields, reducing agriculture's environmental footprint, and ensuring food security. These cultivars leverage both modern biotechnological approaches, including gene editing and genetic engineering, as well as natural plant defense mechanisms to protect against

various pathogens and pests. While these crops significantly reduce reliance on chemical pesticides and strengthen agricultural resilience, challenges such as evolving pests and emerging diseases necessitate ongoing research and monitoring (Shafi et al., 2019).

18.5.2 Precision agriculture

It is also known as smart farming. It is a strategy for the management of farming that helps increase the activities of agriculture by using technology and methodologies that are driven by data. It helps to provide a maximum amount of profit to the farmers by the means of increasing the output of the crop and by decreasing the use of fertilizer and water (Finger et al., 2019). The collection of data is the most important part of this type of agriculture. Information regarding to health of crops, conditions of soil, and weather is gathered by the farmers. Drones and sensors are also used. Precision agriculture may create maps of fields that are detailed for tracking changes and differences in the production of crops across different regions. It helps in understanding the need for the management of pests, water, or nutrients in the field areas that are different. According to the different regions' requirements, VRT is used by the farmers that is a variable rate technology. Because of this, resources are used according to the requirement.

Precision agriculture sometimes uses automated equipment, including self-governing tractors and harvesters, that may be programmed to precisely perform predetermined duties. Farmers receive real-time data from IoT, that is Internet of Things, devices, and sensors that track environmental parameters, including soil moisture, temperature, and humidity. They can make prompt and well-informed decisions as a result. Farmers may make forecasts and spot trends that might not be immediately apparent to the human eye by utilizing machine learning (ML), artificial intelligence (AI), and sophisticated analytics. AI can forecast crop illnesses or prospective yields, enabling farmers to take preventative action (Rojas et al., 2016) (Fig. 18.4).

Precision farming has several advantages, such as higher agricultural yields and productivity, lower input costs (like pesticides, fertilizer, and water), resource-saving, sustainable farming methods, better environmental effects due to less chemical runoff, and better decision-making with data in real time (Jones, 2012).

18.5.2.1 Soil health and precision soil management

The foundation of worldwide food safety, environmental resilience, and sustainable agriculture is soil health. The soil's ability to support vegetation, contribute to ecosystem services, and lessen environmental stressors is determined by the complex interactions of its physical, chemical, and organic components. As the field struggles with an expanding population and the effects of climate change, knowledge and monitoring soil health have become critical for making well-informed decisions about agricultural techniques and land management (Balafoutis et al., 2017). In the past, assessments of the health of soil were dependent on labor-intensive and methods that were very time taking gave a little overview of the conditions despite the soil's

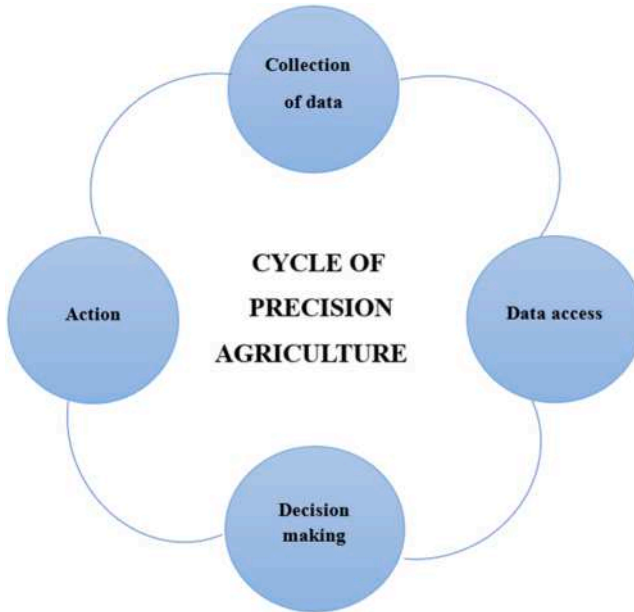


Figure 18.4 Cycle of precision agriculture.

kingdom understanding. With time a new technology came. The development of these sensor technologies gives real-time information on the properties of soil such as the range of nutrients, temperature, and content of moisture. Technologies like these help farmers to make decisions that are driven by data and are accurate. It helps in reducing the impact on the environment (Thakur et al., 2012). Best management practices tailored to the unique conditions of individual agricultural fields. The technological expertise and knowledge underpinning: precision agriculture plays a critical role in the advancement of management of soil and crop practices. Some of its most important elements that support this are sampling of soil; farming that is focused on soil; cultivation that is specific to the site and mapping of yield (DeFries, 2008).

In today's agriculture, machinery in the field that is automated is becoming indispensable for the production of crops. The efficacy of the technology that is geospatial is dependent on the collection of data that is accurate, examination, and data interpretation for decision-taking guide (Khanal et al., 2020). One of the most important elements of geospatial technologies is remote sensing; it is used for capturing data and imagery of the surface of the earth and the activities of humans. Some platforms for example Google Earth are transforming the sharing of data that is geospatial, making it easy for the applications of agriculture access (Frimpong et al., 2023).

- Soil characteristics, such as soil type, pH, electrical conductivity (EC), MC, nutrient availability, and compaction.

- Crop characteristics, including canopy coverage, plant density, pest and disease presence, nutrient needs, hybrid performance, and stress levels.
- Weather predictions that inform optimal farming practices.

Observations of remote sensing have been geo-referenced in a database that is GIS that has made data on remote sensing important to precision agriculture. These types of datasets can be converted into data that is spatial by the help of the tool GIS and the Kriging method. Software GIS evolves data that is spatial into the maps that are digital, which helps in defining zones of management in a farm (Bhatt et al., 2019).

18.5.2.2 Crop yield forecasting and optimization

Estimating the yield of crops is one of the most important tasks but not a simpler one that is important for the intensification of agriculture that is sustainable. Forecasts of crop yield that are accurate benefit most of the stakeholders in the field of agri-food along with farmers.

The yield of crops is impacted by many factors such as conditions that are environmental and practices of management (Maestrini et al., 2022). Various strategies are used for the prediction of the yield of crops such as surveys of fields, models of growth of crops, and methods of statistics (Muruganantham et al., 2022).

ML has appeared to enhance predictions of crop yield. Just like methods of statistics approaches of ML can also be used for incorporating the outputs from the field surveys (Van der Velde & Nisini, 2019). Several advantages of field surveys are used for capturing the relationships that are nonlinear and for reducing the amount of variance present. ML has so much potential; it is used for delivering results that are accurate, and predictions of crop yield are dependable; it is possible through the integration of methods that are traditional (Paudel et al., 2022). There are several systems that are of large scale and are for yield of crops, for example, MARS Crop Yield Forecasting System. These types of systems depend on models of statistics which help in incorporating data of weather and historical statistics of yield. The system is very effective but sometimes fails to integrate with the methodologies of ML. By the integration of these ML methodologies, we can get accurate predictions along with efficiency that will help crop yield new generation systems that are forecasting (Wally, 2021).

18.5.3 Digital tools for climate-smart decision-making

For monitoring, accessing, and verification of the impact of climate on productivity, digital tools are very important. With the development of sensor technologies decision-making that is driven by data has been enhanced. This has helped garnered to make decisions on time, have the right to choose, and also has helped to increase productivity. It also supports the production of climate-smart agriculture (Quarshie et al., 2023). Digitilization of climate-smart agriculture will help in enhancing Digital Agricultural Tools and Services (DATs) by including solutions of data that enhance adaptation of climate. The studies show that radio, phone features Yahya re basic, and TVs are mostly used for this. Rural Farmers are not aware of these advanced tools

like drones; due to which apps in smartphones and gauges of rain still are not that much accessible and also due to lack of affordability (Bajpai et al., 2019). To farmers, DATs, that is, Digital Agricultural Tools and Services, is just available for the purpose of finance that is agri-digital and for procurement that is digital. Practices in the market that are aligned by CSA, for example, e-commerce in agriculture remain inadequately utilized because of less amount of interaction with services.

Because of less knowledge and training that is not sufficient regarding the practices of CSA along with DATs emergence of solutions that are advanced is not taking place. In rural areas, because of cost that is high, inability to access and insufficient infrastructure do not support the emergence of Digitilization of climate-smart agriculture will help in enhancing Digital Agricultural Tools and services (Mishra & Mishra, 2024). Public–private relationships are very important for increasing access to affordable DATs to the farmers. By introducing partnerships, an imbalance in power that is caused by the tools that are digital should be addressed in rural areas. Among rural area people, it is important to increase and make them aware of the importance and benefit of DATs so that practices of CSA can be adopted in their area (Kumar & Rathore, 2022). DATs have technologies that are so much advanced have solutions that are driven by data and are used for enhancing agriculture's efficiency and productivity. Because this transformation that is digital, the system of production and chains of supply and the lives of people in the areas that are rural are getting revolutionized (Ingrao et al., 2023).

With the emergence of these applications, challenges in the field of agriculture are addressed by providing solutions at last time that help in improving the practices of CSA efficiency. These types of tools give support on an immediate basis for a very long period of strategies for the adaptation of climate. Access to TVs, phones, radios, sensors, and drones have the power of supporting functions on a diverse level like management of farms, access to the market, insurance, and services that are financial. By the expansion in the use of these tools, we can enable farmers to adopt practices that are sustainable and can make them secure in the case of a change in climate (Petropoulos et al., 2013).

18.5.3.1 *Smart irrigation*

Water scarcity is a major global challenge, especially since agriculture requires substantial water resources. This underscores the need for systems that optimize WUE. Smart irrigation systems address this issue by estimating and monitoring the depletion of plant moisture levels to operate irrigation systems, replenishing water as necessary while minimizing wastage (Pereira et al., 2009). Soil moisture-based irrigation control systems utilize tensiometric and volumetric methods, which, although straightforward, rely on a soil water characteristic curve that is unique to each soil type. Furthermore, the sensors employed in these systems require regular maintenance to function effectively. Another approach, the intelligent automatic plant irrigation system uses a moisture sensor to automate plant watering without the need for constant human supervision. This system operates using a circuit based on an Op-amp comparator (LM324) and a timer to activate a relay, which controls a motor.

However, its performance is influenced by environmental variations (Playán & Mateos, 2006).

A real-time wireless smart sensor array for irrigation scheduling has also been developed. This prototype utilizes readily available components to measure soil moisture and temperature, specifically for scheduling irrigation in cotton crops. However, its application is limited to specific crops, reducing its versatility. Efficient irrigation scheduling is crucial for water management in agriculture, especially in areas facing water scarcity. Key factors include the amount of water applied, irrigation frequency, and overall water usage. To enhance water efficiency, implementing a well-designed irrigation scheduling strategy is essential. To address this, our project proposes a straightforward system that leverages a microcontroller to automate irrigation for small potted plants or crops, reducing manual intervention to a minimum (Shaikh et al., 2022). Irrigation systems' primary goals are to maximize efficiency and minimize the need for labor and materials. The kind and design of irrigation systems determine which management techniques have the greatest impact. The success of the irrigation system is influenced by several well-known issues, including when to irrigate the soil, how much water is appropriate, and how to increase efficiency. There are numerous factors to consider when choosing an irrigation system, such as the type of crop, the farmer's and farm's location, and the season. These considerations need to include crop specifications, soil and topographic characteristics, system compatibility with the farm's best services, economic viability, and some societal restraints (Jiang et al., 2024). The widespread adoption of IoT technology in agriculture, fueled by advancements in digital technology and embedded sensors, has led to the continuous evolution of sensor designs. Modern sensors are becoming increasingly intelligent, compact, and integrated. A diverse array of agricultural sensors, including those for soil, weather, crops, and water, offer a broad-spectrum of functionalities. These multifunctional sensors play a vital role in collecting essential data to enhance agricultural productivity (Shabbir & Anwer, 2018).

Irrigation systems fall into three main categories:

Pressurized distribution: Water is transported and dispersed throughout the land surface by networks of pressurized pipes, and the key elements of pressurized systems are a trickle, sprinkler, and array of the same systems. Also, new features like center-pivot sprinkler systems offer a variety of specific system designs. **Distribution of gravity-flow:** systems that rely on gravity-flow transport and disperse water at the field level via the free-surface flow regime overland. These surface irrigation techniques are divided according to their configuration and operational requirements. **Distribution of drainage flow:** it is uncommon to find an irrigation system that uses drainage control-sub-irrigation.

18.5.3.2 Artificial intelligence and machine learning for crop modeling

AI algorithms have demonstrated significant potential in understanding the dynamics of soil moisture within the soil–plant–atmosphere system, offering insights that can

be integrated into cost-effective control systems for optimizing irrigation scheduling. Research done recently investigated the NN models, that is neural network for the extraction of the knowledge from the RZWQM2 that is the Root Zone Water Quality Model—it is a model of agriculture system for predicting the moisture present in the soil in the root zone of the plant during the season of growing (Boppiniti, 2019).

AI is the use of cognitive capabilities of humans by machines that makes them able to do work or tasks, for example, natural language processing that is NLP and making decisions by the systems that are expert. There are three processes by which AI is being operated. First is learning; in which data are acquired, and algorithms are created. Second is reasoning, in which algorithms that are appropriate are selected for achieving the outcomes that are desired. Third is self-correction, in which algorithms are being corrected for achieving accuracy. Traditionally AI has been linked with areas like healthcare and finance, but now it has been also applied to the field of agriculture that is helping to increase creativity in the practices of agriculture (Singh et al., 2022).

ML is an important AI subset that employs mathematical along with statistical techniques for the identification of patterns present in datasets and for making decisions. Methods of ML are of three types. First is supervised learning; in which models are trained on datasets that are labeled for mapping variables of input for targeting the outputs with the help of algorithms like decision trees. Second is unsupervised learning, in which datasets that are unlabeled are analyzed for uncovering the patterns that are hidden. Third is reinforcement learning, in which systems are trained to interact with the surroundings for the optimization of outcomes. It is useful in decision-making that is real-time (Farooque et al., 2022).

Algorithms of ML are used in agriculture for the management of irrigation and are used for various applications, including irrigation management. NN method that is irrigation-based is used for calculating rates of irrigation that are required for restoring the moisture present in the soil. It is known to have accurate moisture in soil predictions (Dhanaraju et al., 2022). Planning of irrigation that is efficient is also dependent on Eto, that is, Evapotranspiration forecasts, which are essential for water resource management. Advanced algorithms of deep learning along with an LSTM network that is Long short-term memory have been used for this use (Coglianese & Lehr, 2016). With the help of these models, predictions of Eto that are precise have been enabled, which helps and supports practices of smart farming aiming at the conservation of resources like fertilizers and water along with an increase in the yield, it integrates technologies that are advanced like IoT sensors. Monitoring of moisture present in the soil, temperature, and conditions of the environment, allowing farmers to make decisions on the aspect of irrigation and harvesting is being done by the sensor IoT (Dey et al., 2019).

The use of ML has taken place in many other areas also, by having an impact on making decisions in education, healthcare, and the development of urban areas. With the development of technologies that are driven by AI like ChatGPT, we can see ML impact across so many industries. With time models of ML are evolving and it is said and believed that by time they will help by being the catalysts that are so powerful for

the innovation in technology, with its potential advancements in the areas of optimization of agriculture (Mba & Ogbonnaya, 2022).

18.6 Funding opportunities

Several ways can be employed for financial support to CRA which may include research grants, charitable groups, international climate funds, and government programs. There are subsidies and grants that are available for enterprises centered on CSA techniques that may include varieties like epithet-resistant crops and sustainable water practices from organizations of government like the US Department Of Agriculture (USDA) and the European Union's Horizon Europe. There are many funding sources available internationally such as the Global Environment Facility and The Green Climate Fund (GCF) that support the developing nations in implementing climate adaptation plans and primarily focusing on the ones which a level of agricultural resilience to climate change. The private sector investments that are done via venture capital and impact investing are being targeted by climate-resilient crop varieties and other agricultural technology. There are several groups or agencies coming ahead like CGIAR, that is., Consultative Group On International Agricultural Research so as to increase the advancement in the field of science. An alliance named CGIAR helps in terms of finance-related matters for agricultural research which focuses on enhancement in food security, decreasing poverty, and boosting climate change resilience. The main goals of CGIAR include the creation of new agricultural technology, the development of crop varieties, and sustainable agricultural practices. Several examples include studies on climate adaptation techniques, pest management practices, and smart-crop varieties which are heat, stress, and drought resistant. Funding for research on agroecological farming methods, crop genetic modification for drought and heat resistance, and soil carbon sequestration are a few examples (Martins et al., 2024). There has been an expansion in the funding opportunities for climate-resilient agricultural projects so as to include philanthropic foundations that are significantly becoming a part of small-scale programs and community-based projects that focus on increasing sustainable agriculture in case of climate change. Several websites like Indiegogo, Kickstarter, and GoFundMe help people collaborate and generate funds for CRA initiatives. Local inventiveness that contributes to sustainable agriculture practices, climate-smart technology, and agroforestry can be examples. Expanding and leveling up agricultural solutions that assist farmers, decrease environmental impact, and increase food security requires opportunities in the financial sector. (Abbass et al., 2022).

Several ways can help in funding CRA which can include investments from the commercial sector, research funding, and government. These funding sources play a critical role in the development and growth of agricultural solutions that help farmers adapt to the challenges posed by climate change. The goal of creating sustainable and productive agricultural systems is to provide environmental resilience and food security in the face of global warming (Fita et al., 2015).

18.7 Research prospects

The future of CRA depends on creative research that can address issues brought on by climate change, such as increasing temperature fluctuations, water scarcity, extreme weather events, and shifting pest and disease patterns (Sharma & Behera, 2020). Developing crop varieties that are resistant to flooding, salt, drought, and heat is one of the most fascinating scientific subjects. Advances in genetic modification and gene editing, like CRISPR, could enable the production of resilient crops. The primary objective of the research is to identify the genes responsible for drought tolerance, heat resistance, and improved nutrient utilization efficiency. The objective is to breed crops that can tolerate climate-related stressors, grow with less water, and sustain extreme temperatures without sacrificing productivity or nutritional value. Resilience of the climate is dependent on crop varieties that can withstand challenges which may include drought, high heat and insect pressure. Scientists are exploring methods to enhance crops' ability to withstand multiple environmental challenges simultaneously (Et-taibi et al., 2024). Healthy soils are essential for retaining water, supporting nutrient cycling, and boosting crop yields under stressful conditions. Regenerative agriculture innovations, such as agroecological practices, cover cropping, and reduced tillage, aim to restore soil organic matter, enhance biodiversity, and improve carbon sequestration. These approaches also contribute to reducing the agricultural sector's carbon footprint. In case of boosting storage of carbon in soil which helps in enhancement of soil fertility. Scientists are exploring strategies to enhance soil carbon storage, which improves soil fertility and helps mitigate climate change. Techniques such as agroforestry, deep-rooted plants, and biochar application show promise in increasing soil carbon sequestration (Wilson & Lovell, 2016). As water scarcity becomes an increasingly pressing issue, research on smart irrigation systems that integrate sensors, real-time data, and weather forecasts is crucial. Precision irrigation optimizes water usage by delivering it precisely where and when it is needed, reducing waste and enhancing crop yield per unit of water. Future research will primarily focus on developing more efficient irrigation technologies and methods that conserve water while maintaining high agricultural productivity (Fahad et al., 2021). Agroforestry, which combines trees with crops and livestock, is a valuable approach to enhancing agricultural resilience. Trees contribute to water retention, increase biodiversity, serve as windbreaks, provide shade, and help prevent wind erosion. Key research areas focus on improving biodiversity, strengthening agriculture's ability to withstand extreme weather conditions, and optimizing agroforestry systems for effective carbon sequestration (Banga & Kang, 2014).

To expand these advancements and ensure agriculture thrives amid future climate challenges, collaboration across scientific disciplines and key stakeholders—including farmers, governments, researchers, and the corporate sector—is essential. The focus on CSA will continue to grow, integrating strategies for both climate change mitigation and adaptation. CSA includes measures such as reducing fertilizer-related emissions, improving soil carbon sequestration, and optimizing nutrient management (Dagar & Yadav, 2017).

18.8 Conclusion

The importance of CRA cannot be overstated, especially in the face of a rapidly changing climate. Traditional farming systems are encountering unprecedented challenges due to rising global temperatures, unpredictable precipitation patterns, and the increasing frequency of extreme weather events. The demand for innovative solutions to ensure the long-term resilience, sustainability, and productivity of agricultural systems has never been more urgent (Tomich et al., 2011). Advancements have been made in the field of CRA, particularly in developing crop varieties that can withstand various environmental challenges such as heat, drought, and salinity. Through both traditional breeding techniques and modern biotechnologies like gene editing, genetic innovations are enabling the production of crops with enhanced resilience to climate-related stresses. These developments pave the way for sustaining food production even in increasingly extreme environments. However, developing climate-resilient crops alone is not a complete solution. A holistic approach requires integrating crop genetics with sustainable agricultural practices, efficient water management, soil health improvement, and effective pest and disease control strategies (Huo et al., 2020). Alongside genetic advancements, the research community is increasingly acknowledging the importance of agroecological practices and landscape-scale adaptations in building resilient farming systems. Sustaining long-term resilience requires the adoption of diverse cropping systems that enhance biodiversity and ecosystem services, along with the integration of trees into farming practices, as exemplified by agroforestry. Precision agriculture, driven by big data, remote sensing, and AI, offers a transformative approach to farming by providing farmers with real-time insights into weather conditions, crop performance, and soil health, allowing for more efficient and adaptive decision-making (Fig. 18.5).

Even with the advancements, there are still many obstacles to overcome. The complexity of climate change and its varied effects on various parts of the world call for a focused study that considers local vulnerabilities as well as the opinions and expertise of farmers, especially smallholders. To ensure that disadvantaged communities are not left behind in the quest for technical solutions, CRA must be placed within a larger context of social equality, environmental sustainability, and food security (Hussein El Fadaly, 2023). Addressing the global challenges of CRA would require a multipronged approach that incorporates government policy, business sector involvement, international cooperation, and community engagement. Funding sources such as international climate funds, grants for climate adaptation, and public-private partnerships are crucial to the research and use of climate-smart agricultural practices. Effective scaling of climate-resilient solutions will need collaboration across disciplines, industries, and geographic regions. The future of CRA is obvious, but it calls for ongoing investment, interdisciplinary research, and innovation. By the decrease in the effects of climate change, the shift to resilient agricultural systems will provide more productive, sustainable, and just food systems globally. A potential foundation for adjusting agriculture to the changing climate is

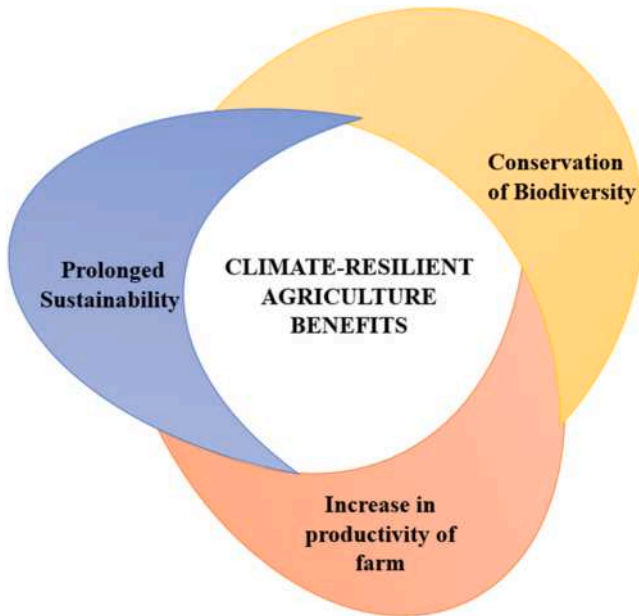


Figure 18.5 Climate-resilient agriculture benefits.

provided by the combination of genetic innovation, sustainable farming methods, and technological improvements, guaranteeing that agriculture will continue to be a vital component of global food security in the twenty-first century and beyond.

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Sustainable agricultural practices using beneficial fungi under changing climate scenarios

19

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19.1 Introduction

The connection of agriculture, climate change, and sustainability has emerged as a critical focal point in global discourse, as humanity confronts the challenges of ensuring food security under the growing threats of environmental degradation and

climate change (Ortiz et al., 2021). As a result, conventional farming methods are being reconsidered and updated to become more resilient and sustainable (Okoronkwo et al., 2024). Over the past few decades, increased research funding has led to innovations that have improved crop adaptation to deteriorating soil health and climate stresses. The use of soil microbes is one of them. In addition to influencing the interaction between soil microorganisms and their function in generating biofertilizers and biopesticides, they are utilized as microbial inoculants and consortia to alleviate the effects of climate change on crop yields (Inbaraj, 2021; Kavadia et al., 2020).

The obvious effects of climate change manifest numerous impacts such as altered precipitation patterns, rising temperatures, increased frequency of extreme weather events, and shifts in pest and disease dynamics (Guo et al., 2021). These aggravate soil erosion, environmental degradation, and the loss of biodiversity in addition to endangering agricultural productivity (Eekhout & de Vente, 2022; Habibullah et al., 2022). Therefore, in order to reduce the risks associated with climate change and to advance ecological resilience and sustainability, creative and adaptable agricultural practices should be continuously revised. Therefore, innovating means of harnessing the potential of beneficial microbes in the environment presents a promising prospect for sustainable agricultural practices and food security despite the challenges posed by climate change (Singh et al., 2023). Fig. 19.1 explains some impacts of beneficial fungi in sustainable agricultural practices.

Beneficial fungi, including a diverse array of symbiotic and endophytic species, offer a natural, compelling solution in this context. Fungi form intricate relationships with plants, aiding nutrient uptake, disease suppression, and stress tolerance. Also, they contribute to soil health, carbon sequestration, and ecosystem stability, offering multifaceted potential that can be exploited for sustainable agriculture (Alori et al., 2017; Eze et al., 2024). In light of the current climate change era, this study examines the diverse functions of beneficial fungi in sustainable agricultural practices. It is talked about how crucial it is to modify cropping techniques in response to climate change challenges.

19.2 Impacts of climate change on sustainable agricultural systems

Changing climate conditions can substantially affect agricultural productivity and food security (Yadav et al., 2018). Variations in temperature, humidity, and precipitation can cause growing seasons to be disrupted, crop yields to be decreased, soil microbial activities that promote plant growth to be increased, and the prevalence of pests and diseases to rise. Fisheries, aquaculture, and livestock production are all impacted by climate change, which may cause problems with the availability of food (Cheng et al., 2022). This might have unintended detrimental effects on people's health by leading to starvation, infections from contaminated water, illnesses brought on by the heat, and various degrees of mental health issues (Myers & Bernstein, 2011). Rocha et al. (2022) noted that the population of humans is most susceptible to the effects of climate change. This is due to the fact that the effects of climate change, such as heat waves, extreme weather, and altered disease patterns, can weaken immunity in people, raising

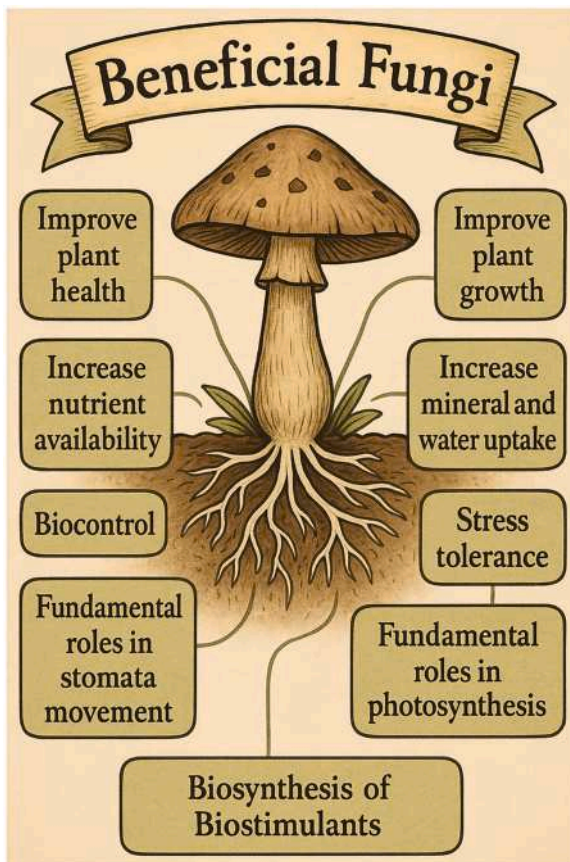


Figure 19.1 Impacts of beneficial fungi in sustainable agricultural practices.

their risk of developing respiratory issues, heat-related illnesses, vector-borne infections, waterborne infections, and other infections (Ebi et al., 2021). Susceptible populations, including the elderly, children, and marginalized communities, are particularly at higher risk of being affected by climate change-related stresses, leading to loss of livelihood, chronic exposure to pollutants and extreme weather patterns, epidemiological illnesses, and adaptive challenges to the changing socioeconomic landscape (Rocklöv & Dubrow, 2020).

Crop productivity is negatively impacted by climate change in a number of ways, including decreased soil fertility and crop yield, limited soil water availability, increased soil erosion, and increased pest spread (Tajudeen et al., 2022). According to Grigorieva et al. (2023), the negative impacts of climate change are expressed in terms of reduced crop yields and crop area.

Also, the impacts of climate change can have significant economic consequences (Kalkuhl & Wenz, 2020). Circular economic growth can be significantly slowed down by a number of factors, including damage to infrastructure, higher healthcare

costs, disruptions to agriculture and food production, and the loss of coastal features and tourism revenue. These consequences may exacerbate already-existing disparities by causing social and economic inequality. The adverse effects of climate change encompass financial setbacks, escalated expenses for labor, and equipment (Grigorieva et al., 2023).

Dangerous climatic events such as flooding, extreme heat, and drought have led to soil degradation, which results in low crop yields (Agbola & Fayiga, 2016). Climate change negatively impacts crop productivity by decreasing soil fertility, and increasing soil erosion (Tajudeen et al., 2022). Due to changes in the ideal temperature ranges, climate change has also jeopardized the survival and integrity of many species, hastening the loss of biodiversity by gradually altering the ecosystem structures.

19.3 Importance of adapting cropping practices to climate change challenges

Adaptation refers to actions designed to increase the ability of individuals and communities to decrease harms from climate change that will occur in numerous parts of human life (Orlove, 2022). Hence, adapting cropping practices means activities aimed at increasing the cropping practice's ability to lessen the harms from climate change. Adaptation of cropping practices to climate change includes changes in a cropping practice in response to variations in climate situations (Akinagbe & Anugwa, 2015). Cropping practices can adapt in response to a series of events, such as temperature and precipitation levels, that cause droughts (in terms of intensity and/or frequency), which have an impact on crop yield (Smit et al., 2000). Crop varieties and management, innovative breeding techniques and changes in land use, water and soil management, agronomic practices, farmer training, and knowledge transfer are some of the crop practices that could be adjusted to the challenges posed by climate change (Grigorieva et al., 2023).

According to Akinagbe and Anugwa (2015), Farmers frequently use the following adaptation strategies for their crops: using drought-tolerant crop varieties; crop diversification; altering cropping patterns and planting dates; conserving soil moisture through appropriate tillage techniques; increasing irrigation efficiency; and afforestation and agroforestry. The United Nations Sustainable Development Goals, which sought to safeguard the environment and guarantee that everyone lives in peace and prosperity, will be achieved through cropping practices that are adjusted to the challenges posed by climate change. sustainable cultivation of food (Çakmakçı et al., 2023). A key factor in reducing the adverse effects of climate change will be cropping practices adaptation, which may involve changes to field-scale management techniques (Lehmann et al., 2013).

Additionally, some of the effects of climate change are occurring more quickly than previously thought, and cropping practices will need to adapt to these trends if they are to continue (Rahmstorf et al., 2007). Differences in annual rainfall, average temperature, heat waves, alterations in weeds, pests or microbes, universal alteration

of atmospheric CO₂ or ozone level, and instabilities in sea level, all due to climate change, impede total crop production and compromise food security worldwide (Raza et al., 2019). By using specially designed fertilization regimes in single-crop cultivation systems, cropping practices can be adjusted to the challenges posed by climate change. This reduces the need for inputs, water waste, fossil fuels, and unharvested products, all of which lower emissions and boost net productivity (Turner-Skoff & Cavender, 2019). Additionally, by lowering the amount of methane released during animal production, choosing plant-based protein sources (like pulse crops) rather than animal-based proteins lowers agricultural greenhouse gas emissions (Volk et al., 2023). Cropping practices that are adjusted to the challenges posed by climate change will: lower exposure to damage risk; increase resilience to inevitable damage; and enable the cropping system to seize new opportunities (Akinngbe & Anugwa, 2015).

19.4 Activities of beneficial fungi that enhance crop and cropping system efficiency in the climate change era

Beneficial fungi adopt strategies, either direct or indirect, to help crops and cropping systems in the face of climate change. Production of phytohormones, nitrogen fixation, phosphate solubilization, siderophore formation, and antimicrobial metabolites are all part of the direct beneficial mechanism (El Enshasy et al., 2020).

Endophytic fungal annexation encourages physical changes and alters gene expression in the plants, thus elevating plant productivity through higher photosynthesis rate, encouraging the growth of the shoots and roots, improving uptake and nutrient use efficiency, and providing resistance to biotic (pathogens and pests) and abiotic stress (drought, salinity, high temperature, high CO₂, and metal toxicity) (Grabka et al., 2022). Beneficial fungi act as biostimulants to yield certain bioactive compounds, phytohormones, phosphate solubilization factors, etc., to improve root growth, seed germination, and plant growth promotion (Rustamova et al., 2022). Many fungi, such as *Penicillium*, *Aspergillus*, *Curvularia*, *Trichoderma*, *Mesorhizobium*, *Aspergillus fumigatus*, *Aspergillus niger*, *Alternaria thlaspi*, *Metapochonia rubescens*, have been identified and reported to have ability to solubilize and mobilize phosphorus, potassium, and zinc salts thereby boosting plant metabolic activity, plant growth resulting in high crop production (Haro & Benito, 2019; Mehta et al., 2019; Yung et al., 2021). They execute phyto stimulation via lowering plant hormone ethylene levels by 1-aminocyclopropane-1-carboxylate deaminase (ACC), escalating plant growth (Singh et al., 2015). Additionally, they break down biomass and reuse it into the environment, which increases the host's availability of nitrogen and increases its uptake of zinc and phosphorus, leading to phyto immobilization (Yung et al., 2021).

Through the immobilization of osmolytes and the stabilization of membrane ion conductivity under stress conditions brought on by climate change, phyto immobilization ultimately increases plants' ability to withstand abiotic stresses (Verma et al., 2022). Beneficial fungi disrupt pathogens' quorum sensing (QS) by inhibiting the

production of signal molecules that initiate infections. Take, for instance, the production of QS inhibitors that can break down QS signal molecules, such as chitinases, pectinases, and lactonases. These inhibitors prevent pathogen invasion and lead to reduced plant disease symptoms (Saeki et al., 2020). *Curvularia geniculata* mediates plant growth through phosphate solubilization and phytohormone production (Priyadharsini & Muthukumar, 2017).

The incidental beneficial mechanism includes resistance to abiotic and biotic stressors (modifying the metabolism process), biocontrol, etc. (Singh et al., 2021). Beneficial fungi defend plants indirectly by triggering a defense response or promoting plant growth (Zubair et al., 2021). As a result, the host undergoes a wide range of biochemical and molecular defensive processes that serve as a defense mechanism against numerous pathogens (Ayaz et al., 2023). Endophytic fungi potentially execute munificent global roles in the host plant via phytostimulation, phytoimmobilization, phytostabilization, phytotransformation, phytoremediation, and biocontrol (Adeleke et al., 2022b). They are reported to produce secondary metabolites, which include bioactive antimicrobial siderophores, which may execute defense against various pathogens (Srinivas et al., 2020). They inhibit the pathogens' pathogenicity over different materials such as lipopeptides, biosurfactants, bacteriocins, volatiles, and enzymes that have antimicrobial properties by reducing the development or metabolic activity of pathogens (Babalola, 2010).

Under chilling stress, *Funneliformis mosseae* inoculation significantly improved the content of related secondary metabolites, including phenols, flavonoids, lignin, DPPH activity, and phenolic compounds (Chen et al., 2013). *Glomus mosseae* under low temperature stress increased leaf activities of superoxide dismutase, ascorbate peroxidase, guaiacol peroxidase, ascorbate, and glutathione, but decreased leaf concentrations of malondialdehyde, and hydrogen peroxide in crops (Liu et al., 2017).

19.5 Benefits and efficacy of sustainable agricultural practices using beneficial fungi

Rhizosphere soil fungi, such as *Trichoderma* spp., *Gliocladium virens*, *Penicillium digitatum*, *Aspergillus flavus*, *Actinomucor elegans*, *Podospora bulbillosa*, and arbuscular mycorrhizal fungi, can improve the growth of the shoots and roots of crop plants, the germination of seeds, the production of chlorophyll for photosynthesis, and the copious production of crops (Adedayo & Babalola, 2023a). Applications of beneficial fungi overwhelm the usage of agrochemicals and likewise prevent plants from biotic and abiotic stresses (Malgioglio et al., 2022). The beneficial fungi improve plant root extension, encourage plant growth development (seed germination and seedling strength and photosynthetic efficiency), protection from various kinds of phyto-pathogens, and also support soil improvements (Kumari et al., 2021). Plant growth-promoting fungi could suppress plant diseases by producing inhibitory chemicals and inducing immune responses in plants against phytopathogens, and have therefore proven to be effective biofertilizers and biopesticides, and are considered a feasible, attractive economic approach for sustainable agriculture

(El-Saadony et al., 2022). As stated by Muthuraman and Murugaragavan (2020), beneficial fungi conjointly play a basic role in different physiological processes as well as mineral and water uptake, chemical change, stomata movement, and biosynthesis of compounds termed biostimulants, auxins, lignan, and ethylene to enhance the flexibility of plants to ascertain and cope environmental stresses like drought, salinity, heat, cold, and significant metals. Beneficial fungi produce large quantities of bioactive compounds that can be used as agrochemicals for crop protection (Ayaz et al., 2023). Table 19.1 reported some of the benefits of using beneficial fungi for sustainable agricultural practices in a changing climatic scenario

19.6 Economic and environmental feasibility of adopting fungi in sustainable agriculture

In the majority of cases, climate-smart systems that incorporated beneficial fungi outperformed the conventional control, with some even achieving a yield gain of over 60% (Thierfelder & Mutenje, 2018). Due to their biomass, hyphal network, and longer life cycle, fungi are more advantageous over bacteria for bioremediation of polluted agricultural soil (Kour et al., 2024). Utilizing arbuscular mycorrhizal fungi as a biofertilizer increases nutrient uptake, stimulates plant growth hormones, and expedites the decomposition of organic wastes, all of which can increase crop yield (Osemwegie et al., 2021). In nature, fungi are commonplace, and their various strains give their species greater specificity against pests and illnesses. They are self-sustaining because the infection spreads by means of spores, which are generated in vast quantities and persist so long as the right conditions for growth are present. As a result, application costs are also decreased (Singh et al., 2018). A deeper understanding of the physiological responses of these microbes to stress can help develop a more robust and resilient agroecosystem, even though research supports the use of mycorrhizae and fungal endophytes as an environmentally friendly alternative to combat drought stress (Raghuwanshi, 2018). With their varied functional diversity and dispersal mechanisms, fungi constitute a significant and diverse component of the majority of ecosystems on Earth. The expanding body of knowledge regarding microbial biogeography is demonstrating how different fungal assembly patterns and processes are from bacterial ones. Their ability to successfully adapt and impact the environment is rooted in their multifaceted capacity to interact tempo-spatially with an increasingly diverse array of physical, chemical, and biological ecosystem components (Bahram & Netherway, 2022). Furthermore, their ubiquitous distribution, diverse ecological roles, remarkable biological diversity, and high sensitivity have favored them as one of the most important groups of environmental bio-indicators (Warnasuriya et al., 2023). Suffice it to say that their existence, quantity, and nature can be used to make inferences about the quality of the environment or detect environmental contaminants by less rigorous laboratory analyses or in situ visual inspections. As a result, they aid in soil fertility by breaking down plant and animal waste through enzymatic processes. Many also interact with soil fauna and saprophytic bacteria to maximize access to nutrients from rocks and organic remains,

Table 19.1 Benefits of using beneficial fungi for sustainable agricultural practices.

Beneficial fungi	Climatic factor/ stress condition	Crop	Effects	References
Ascomycetes	Semiarid	Maize	Improves physiological attributes of maize	Akinola et al. (2023)
<i>Trichoderma</i> species	Management of root rot diseases	Tomato	Improved crop health and productivity	Olowe, Nicola, Asemoloye, Akanmu, Babalola (2022)
<i>Trichoderma</i> species	Pathogenic <i>Fusarium</i> species	Maize, banana, and cassava	Inhibit the growth of <i>Fusarium</i> pathogens in vitro.	Olowe, Nicola, Asemoloye, Akanmu, Sobowale et al. (2022)
<i>Trichoderma koningii</i> , <i>Purpureocillium lilacinum</i> , <i>Mortierella alpina</i>	Biotic stress: Powdery mildew disease caused by <i>Oidium neolycopersicum</i>	<i>Solanum lycopersicum</i>	The fungi isolate promotes the production of tomatoes from Healthy rhizosphere soil and reduces the phytopathogen activities	Adedayo et al. (2023a)
<i>Trichoderma</i> spp., <i>Gliocladium virens</i> , <i>Penicillium digitatum</i> , <i>Aspergillus flavus</i> , <i>Actinomucor elegans</i> , <i>Podospora bulbillosa</i> , Arbuscular mycorrhizal fungi <i>Ascomycota</i> and <i>Basidiomycota</i>	Abiotic and biotic conditions	<i>Solanum lycopersicum</i> , <i>Cucumis sativus</i> , <i>Zea mays</i> , <i>Oryza sativa</i> , <i>Triticum aestivum</i> , <i>Zea mays</i> , etc.	Plant growth-promoting fungi promote abundant production of various crops	Adedayo and Babalola (2023a)
	Plant diseases; <i>Oidium neolycopersicum</i>	<i>Solanum lycopersicum</i>	Fungi produce plant-growth-promoting genes that contribute to the abundant production of tomatoes and inhibit or eradicate disease invasion	Adedayo et al. (2023b)

<i>Arbuscular mycorrhiza</i> fungi, <i>Trichoderma harzianum</i>, <i>Purpureocillium lilacinum</i>, <i>Metarhizium anisopliae</i>, <i>Penicillium spp.</i>, <i>Aspergillus sp.</i>, <i>Coprinellus radians</i>, <i>Neurospora spp.</i>, <i>Paecilomyces spp.</i>, <i>Epichloë typhina</i> and <i>Curvularia protuberata</i> <i>Rhizobium spp.</i>, Arbuscular mycorrhizal (AM) fungi, <i>Metarhizium brunneum</i>, <i>Sargassum vulgare</i>, <i>Acanthophora spicifera</i>, <i>Ascophyllum nodosum</i>, <i>Trichoderma spp.</i>, <i>T. viride</i>, <i>P. chrysogenum</i>, <i>Cladosporium cladosporioides</i>, <i>Aspergillus fumigatus</i> <i>Bradyrhizobium spp.</i>, <i>Filobasidiella</i>, <i>Ustilago</i>, <i>Tilletia</i>, <i>Metarhizium</i>, <i>Sordaria</i>, <i>Coprinopsis</i>, <i>Sclerotinia</i>, <i>Gibberella</i>, <i>Phaeosphaeria</i>, <i>Podospora</i>, <i>Ajellomyces</i>, <i>Aspergillus</i>, <i>Aspergillus fumigatus</i>, <i>Saccharomonospora sp.</i>, Ascomycota, Basidiomycota, and Blastocladiomycota	Abiotic and biotic stress	<i>Solanum lycopersicum</i> , <i>Zea mays</i> , <i>Arabidopsis thaliana</i>	Promote the production of the crop and prevent biotic including plant diseases, and abiotic stress including heavy metal toxicity, drought, salinity, extreme temperature	Babalola et al. (2022)
	Abiotic stress	Crop plants	Fungi implement Biostimulant activities in various crop plants	Adedayo and Babalola (2023b)
	Biotic and abiotic stress	<i>Vigna unguiculata</i> , <i>Helianthus annuus</i> , <i>Zea mays</i> , <i>Oryzae sativa</i>	Endophytic fungi improve the growth as well as abundant production of crops	Babalola and Adedayo (2023)
	Biotic stress (plant diseases); <i>Oidium neolyopersicum</i>	<i>Solanum lycopersicum</i>	They contribute to plant growth promotion by improving the health status of the crop plant	Adedayo et al. (2022)

(Continued)

Table 19.1 (Continued)

Beneficial fungi	Climatic factor/ stress condition	Crop	Effects	References
Arbuscular mycorrhizal fungi	Abiotic stress	<i>Triticum spp.</i> , <i>Populus spp.</i> , <i>Zea mays</i> , <i>Pisum sativum</i>	The fungi promote plant growth and development by tolerating the various abiotic stress	Koza et al. (2022)
<i>Trichoderma asperellum</i> , <i>Glomus tortuosum</i> , <i>Glomus ethunicatum</i>	Abiotic stress	<i>Solanum lycopersicum</i> , <i>Zea mays</i> , <i>Vigna radiate</i> , <i>Trifolium repens</i> , <i>Latuca sativa</i> , <i>Thymus vulgaris</i>	Plant growth-promoting fungi relief crops from abiotic stresses	Adeleke et al. (2022a)
<i>Trichoderma viride</i> and <i>Penicillium chrysogenum</i>	Soft root disease; <i>Fusarium oxysporum</i> , <i>Aspergillus wenti</i> , <i>Penicillium digitatum</i>	<i>Citrus sinensis</i>	The fungi provide biological control activities against the phytopathogens causing soft rot diseases in sweet oranges	Omomowo et al. (2020)

even though they perform biodegradation functions. For instance, one of nature's forces behind sustainable agriculture is the symbiotic relationship between plants and fungi. Through their interactions with bacteria and other living things, including animals, fungi are able to complete their life cycle in varying degrees of symbiosis. A symbiotic relationship between some bacteria and fungi can help transform atmospheric nitrogen into forms that are useful to biological systems (Rashid et al., 2016). While bacteria are the main nitrogen-fixing organisms, some fungi can play a supportive role in Nitrogen fixation. Mycorrhizal fungi form mutualistic associations with plant roots, enhancing nutrient uptake (Khaliq et al., 2022). In some cases, these mycorrhizal associations can also facilitate the colonization of nitrogen-fixing bacteria. The fungus offers a favorable environment for the bacteria, such as protection from harsh conditions and a carbon source. In return, the bacteria provide the plant with fixed nitrogen in the form of ammonia or other nitrogen compounds.

Fungal hyphae grow beyond the root nutrient depletion zone and are much finer than plant roots. They can access soil pores containing plant essential nutrients that are hitherto inaccessible to their host (Begum et al., 2019; Watts et al., 2023). It is equally logical to hypothesize that the penetrating hyphae, while extending beyond the rhizospheric zone, interact with numerous niches of microorganisms and hyphae from other rhizosphere zones to sustain soil ecological functions, structure, ecophysiology, metabolic dynamism, and soil health. Therefore, harnessing soil fungi's potential to drive soil ecosystem activities is promising for sustainable climate-smart agriculture, reducing reliance on synthetic fertilizers (Clocchiatti et al., 2021).

19.7 Using beneficial fungi to enhance plant growth and resistance to pests and diseases

Beneficial fungi positively impact sustainable agriculture under different climate scenarios as discussed in Table 19.2.

Certain fungi infiltrate the tissues of plants, creating a home for bacteria that fix nitrogen from the atmosphere and convert it into nitrate that is used by plants to grow (Burraroni & Jeon, 2021). Furthermore, Fungi facilitate the uptake of nutrients by plants, improving their capacity to absorb nitrogen, phosphorus, and other micro-nutrients. In order to enhance plant growth and development, fungal hyphae pierce the soil to obtain nutrients that are not accessible to the plant's root system. Plants are also able to withstand a variety of environmental stresses thanks to this symbiotic relationship. It epigenetically promotes the production of bioactive substances that have anti-biotic and antibiotic qualities against pathogens, saline, drought, and high temperatures (Zhang et al., 2023). The plant hosts' defense systems are strengthened by the metabolites, which also make them more resilient to harsh environmental conditions and adaptation. Thus, it is impossible to undervalue the role that fungi play in host plants' ability to withstand disease. Certain endophytic fungi give plants the ability to resist various diseases by producing bioactive compounds with antifungal or antibacterial qualities that inhibit the growth of pathogens (Zeilinger, 2023). Endophytic fungi, for instance, can act as a first line of defense against

Table 19.2 Roles of beneficial fungi under changing climate scenarios.

S/ N	Fungi	Impact	Role of the beneficial fungi	References
1	Mycorrhiza sp., <i>Trichoderma</i> sp., <i>Chaetomium</i> sp., and <i>Gliocladium</i> sp	They enhance plant growth, suppress abiotic stress conditions, and influence a number of biochemical developments and functions	Biofertilizer, Biocontrol agents	Odoh et al. (2020)
2	<i>Glomus fasciculatum</i> , <i>Glomus mosseae</i>)	Augmented the concentration of total phenolic compounds, flavonoids, and phenolic acid contents.	Tool for improving health-promoting compounds in vegetable	Khalid et al. (2017)
3	<i>Glomus</i> spp	Improve plant growth	Biofertilizer	Arya et al. (2018)
4	<i>Aspergillus awamori</i> , <i>Penicillium citrinum</i>	Stimulatory effect on chickpea plant growth.	Biofertilizer	Mittal et al. (2008)
5	<i>Trichoderma asperellum</i>	Increased chickpea (<i>Cicer arietinum</i>) growth parameters in the presence of plant pathogen <i>Fusarium equiseti</i> in chickpea	Biofertilizer, Biocontrol	Adnani et al. (2024)
6	<i>Trichoderma harzianum</i>	Increased plant height, stem circumference, leaf number, total phosphorus in the rubber tree leaves, shoot fresh weight, root fresh weight, shoot dry weight, and root dry weight	Biofertilizer	Promwee et al. (2014)
7	<i>Curvularia geniculata</i>	Superior growth	Biofertilizer	Priyadharsini and Muthukumar (2017)
8	<i>Penicillium</i> sp	Plant growth promotion	Drought-adaptive bioinoculants	Kour et al. (2020)
9	<i>Funneliformis mosseae</i>	Higher fresh weight and dry weight of the crop	Alleviation of chilling stress	Chen et al. (2013)
10	<i>Glomus mosseae</i>	Higher concentrations of soluble sugar, proline, P, and K	Resistance of plants against low-temperature stress	Liu et al. (2017)
11	<i>Gigaspora rosea</i> , <i>Glomus clarum</i> , <i>G. rosea</i> + <i>G. clarum</i>	Higher dry matter and superoxide dismutase and peroxidase enzyme activities	Biofertilizer	Sapelli et al. (2024)

pathogens by colonizing plant tissues and providing a barrier against invasion (Baron & Rigobelo, 2022). Additionally, by boosting the immune response, they can strengthen the plant's resistance to disease. Additionally, they generate compounds that promote plant growth, such as gibberellins, cytokinins, and auxins, which can boost nutrient uptake, encourage root and shoot growth, and increase overall plant vigor. Endophytic fungi have the potential to enhance crop yields, increase biomass, and grow larger root systems (Tripathi et al., 2022).

19.8 Conclusion

In climate change scenarios, beneficial fungi are important for sustainable agriculture in a variety of ways. Their benefits to disease prevention, soil health, sequestration of carbon, and overall ecosystem resilience make them invaluable allies in combating climate change-related agricultural challenges. Agricultural systems that are resilient and sustainable must be developed by putting in place measures that support and maximize the potential of these fungi. Under scenarios of a changing climate, beneficial fungi can play a variety of roles in sustainable agricultural practices, including biofertilizer, biocontrol agents, and abiotic stress bioremediators.

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CLIMATE CHANGE AND AGRICULTURAL ECOSYSTEMS

Second Edition

CURRENT CHALLENGES AND ADAPTATION

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Fully revised to include the latest scientific developments, *Climate Change and Agricultural Ecosystems: Current Challenges and Adaptation, Second Edition* continues to provide vital insights into the complex and dynamic relationship between climate, agriculture, soil, and plants. Building on its proven value in guiding real-world application as well as inspiring further research, this new edition includes new insights and practices. Agricultural ecosystems are highly dependent on weather and climate for the production of necessary foods to sustain human life. Despite leading cutting-edge tools and technologies for developing improved varieties, genetically modified organisms, and irrigation systems, climate change is still a major constraint to agricultural productivity. It takes years to assess the impacts of climate change and vulnerability to it and to prepare proper countermeasures against it. Developing countermeasures drawn based on scientific diagnosis and assessment of the impacts of climate change on agriculture are essential in establishing the vision and administrative policies of future agriculture. This book focuses on recent research and updates on interactions between agriculture, ecosystems, environment, and climate change bringing together ideas and innovations of the latest scientific findings on climate change and enriched by renowned researchers' knowledge and experience in this field. It reflects the importance of acting now on climate change: to eliminate hunger and to enable the agriculture sectors to adapt to climate change.

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