Chapter

Climate-Smart Agriculture for Sustainable Rice Production: Innovations and Practices

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Abstract

Rice is recognized as a global staple food and is crucial for food security. Its production in Africa and many parts of Asia is largely rainfed, which makes it highly vulnerable to climate change threats like flooding, erratic rainfall, rising temperatures, droughts, and greenhouse gas emissions. These factors, along with limited access to resources, hinder sustainable rice farming. To mitigate these risks, adopting climate-smart agriculture (CSA) is essential. Climate-Smart Agriculture enhances the resilience, productivity, and sustainability of rice systems. This chapter outlines the pillars of climate-smart agriculture and examined its relevance to sustainable rice production. Key climate-smart agriculture practices for rice farming highlight practical CSA innovations such as water-saving techniques and improved seed varieties, among others. The chapter further presents successful case studies in Indonesia, India, Vietnam, Myanmar, Laos, Bangladesh, and West Africa. These examples demonstrate how CSA has significantly increased productivity, enhanced environmental sustainability, and improved resource-use efficiency. The common challenges in scaling climate-smart agriculture and the role played by the governments, non-governmental organizations (NGOs), and research institutions in promoting climate-smart agricultural practices in rice production, spanning policy development and funding to community engagement and technology innovation, were also identified. This synthesis aims to guide policymakers, researchers, and farmers in implementing effective CSA practices for climate-resilient rice production.

Keywords: climate-smart agriculture, rice production, climate change, food security, sustainable agriculture, food sustainability

1. Introduction

Rice production systems contribute significantly to the reduction of hunger and poverty across the globe. For many around the world, rice is the primary food crop, surpassing the production of numerous other cereal crops [1]. The United Nations Department of Economic and Social Affairs reported that the world population is expected to reach 9.8 billion, which will require a significant increase in food production, a goal that appears challenging to attain with the existing agricultural practices [2]. The regular consumption of rice is attributed to its rich nutritional profile, such as carbohydrates, calcium, thiamine, iron, folate, and Vitamin B5 and E, which surpasses the levels found in maize, wheat, and potatoes. Studies have established a positive correlation between phenolic compounds and their antioxidant properties, and evidence suggests that these compounds aid in the prevention of diabetes and cardiovascular diseases. Globally, rice production is anticipated to increase to a range of 58 to 567 metric tons by 2030 [3].

Despite the importance of rice production in ensuring global food security, the primary obstacles to achieving global rice production have been identified as persistent crop losses caused by plant diseases and the impact of climate change [4, 5]. Statistics from the period 2022–2024 indicate that China is leading the world in both rice production and consumption, with 145,950 metric tons of milled rice produced in 2022/2023 and 149,920 metric tons consumed in 2023/2024. Other countries reported include India, Bangladesh, Indonesia, Vietnam, Thailand, the Philippines, Burma, Japan, and Cambodia, as well as sub-Saharan African countries such as Nigeria [6]. In these regions, rice yields are projected to decrease 10% or more as a result of climate change, largely driven by rising temperatures, less consistent and/or reduced water supply, and other climate change-mediated changes to agroecosystems such as pests and diseases [7].

Rice production is threatened by drought and flood, which can impact both its quantity and quality, posing a significant risk to those whose livelihood depends on it. China and India are the countries most impacted, accounting for more than half of global production, as both producers and consumers. This has a ripple effect on the global market, affecting millions of households in developing countries that depend on rice as their primary source of food [8]. Rice production in sub-Saharan Africa has been significantly affected by recurring droughts, which is more susceptible to when compared to other crops. In sub-Saharan Africa, rice production is primarily under rainfed conditions that rely primarily on precipitation, making the crop vulnerable to droughts. Climate change intensifies soil salinity, and this greatly affects crop yield and the technical efficiency of rice farming [9].

Adopting climate-smart agriculture (CSA) techniques is essential to sustainably increase agricultural productivity, enhance resilience against climate change, and reduce greenhouse gas emissions in agriculture, specifically to achieve sustainable rice production. Therefore, this chapter aims to explore the climate-smart agriculture techniques in rice production and their associated potential. Also, we discussed case studies of successful climate-smart applications in rice systems.

2. Overview of climate-smart agriculture (CSA)

2.1 Definition and principles of climate-smart agriculture

Climate-smart agriculture is an innovative approach aimed at fostering food security and promoting sustainability in the agricultural system through the development of certain conditions [10]. To achieve food security and sustainable development goals, especially in rice production, at both the global and national levels, climate-smart agriculture techniques serve as a vital solution [11]. In the definition by the Food and Agriculture Organization (FAO), climate-smart agriculture primarily aims at achieving food security and development. However, productivity, adapting, and building resilience and mitigation strategies are identified as the vital pillars/principles in achieving the goals.

The Pillars of Climate-Smart Agriculture

a. *Productivity:* Increasing sustainable agricultural production and incomes by enhancing soil quality.

b. *Adapting and building resilience:* Reinforcement of farmers' resilience to climate shocks while ensuring that the environment is not negatively impacted [12].

c. *Mitigation strategies:* In 2020, 1.3% of total emissions out of 18.4% global greenhouse gas emissions were caused by agriculture and forestry, which was attributed to rice production [13]. Climate-smart agriculture ensures that greenhouse gas (GHG) emissions are reduced or completely removed. This is done by employing mitigation strategies like discouraging deforestation and fostering carbon sequestration (a technique used to capture carbon dioxide and other forms of carbon from the atmosphere) [12, 14].

2.2 Relevance of climate-smart agriculture to rice production

Agriculture and rice production are the key components of the global food supply. With the ongoing climate change, it is essential to tackle the challenges it creates. Climate-smart agriculture is seen as an important tool that enhances agricultural efficiency and sustainability while tackling the challenges [15]. Climate-smart agriculture practices in rice production have a positive impact, including increasing yields, optimizing resource use, and increasing resilience to climate risks. When these practices are implemented, the drive for sustainability and food security is achieved.

Adoption of climate-smart agriculture practices such as improved rice varieties, soil and water conservation techniques, effective and efficient use of pesticides, and adjusting the planting and harvesting dates can increase yields by approximately 15.87% as well as net incomes of farmers [16, 17]. When compared to traditional methods, climate-smart agriculture can help enhance energy use efficiency and reduce gas emissions [18, 19]. Climate-smart agriculture practices such as crop rotation and conservation tillage improve rice production, thereby creating a stronger agricultural system that is resilient to climate risks [12]. The relevance of climate-smart agriculture to rice production can therefore be distilled into four main benefits: increased yields, enhanced economic benefits, resource use efficiency, and resilience to climate risks.

3. Key climate-smart practices for rice farming

Rice production is vulnerable to climate-induced changes, particularly to high temperatures, and this necessitates the development of systems and conventional technologies such as climate-smart agriculture to acclimate to the changing climate [1]. Results from the findings [13] revealed that rice production increases as the adoption of climate-smart agricultural practices increases. Examples of these practices are depicted in **Figure 1**, and they are water management techniques, soil health management, the use of resilient rice varieties, and digital tools and precision farming.

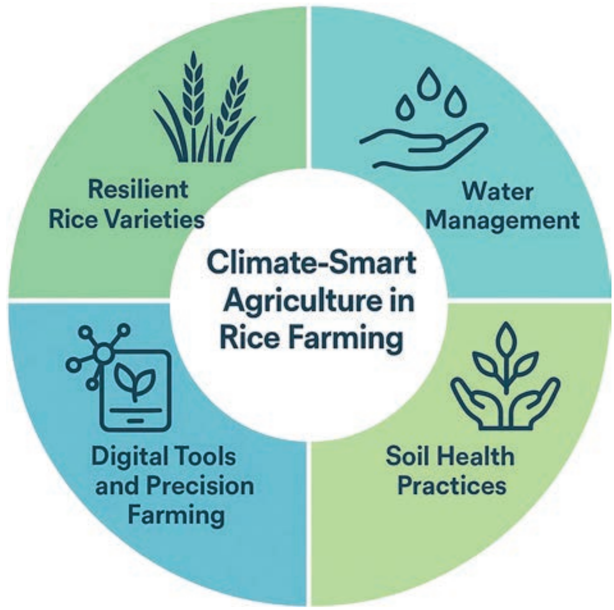

Figure 1.
Climate-smart agriculture practices.

3.1 Water management techniques

The alternate wetting and drying as a water management technique is significant in the enhancement of water efficiency, environmental sustainability, and productivity. In regions facing water scarcity due to climate change, this technique can increase grain yield by 15% during the wet season and 7% during the dry season, reduce water input by 19% in the wet season and 39% in dry season, and water productivity by 46% in the wet season and 77% in the dry season when compared to the continuous flooding techniques [20]. Also, it can help reduce the overall global warming by 40–40% and the emissions of methane by 53%. The system of rice intensification (SRI) has been found to improve rice yield while consuming less water [21]. Other water management techniques include water-saving irrigation, deep-irrigated rice, and aerobic rice. Promoting and adopting these water-saving techniques is essential for sustainable rice production due to increasing water scarcity in climate change scenarios [17, 21].

3.2 Soil health management

Climate-smart agricultural practices such as zero tillage and organic amendments (integrated nutrient management) collectively improve soil properties and mitigate the effects of climate change. These techniques increase soil organic carbon and improve biological quality, such as enzyme activities and microbial biomass [22]. Zero tillage and residue retention enhance soil structure by increasing macro-aggregate stability and carbon health, which are vital for maintaining soil health and productivity [23].

3.3 The use of resilient rice varieties

The use of resilient varieties as a climate-smart agriculture practice is significant in achieving sustainable rice production and increasing yield, which impacts food security and livelihoods of rice farmers [24]. Climate-smart rice varieties, such as drought-tolerant and submergence-tolerant types developed through advanced breeding techniques, have shown improved tolerance to abiotic stresses such as drought, flooding, and salinity [25]. These resilient varieties help to stabilize yields under adverse conditions [26].

3.4 Digital tools and precision farming

The integration of digital tools and precision farming management techniques in climate-smart agriculture significantly impacts rice production. The use of Internet of Things (IoT), machine learning (ML), and Big Data (BD) in rice farming facilitates real-time monitoring and predictive analytics, leading to rice yield estimation, disease monitoring, and more efficient supply chain management [27, 28]. Smart farming as an agricultural management strategy focuses on leveraging data effectively gathered about rice production, rather than emphasizing data storage, applications, and accessibility [28]. Precision farming techniques, for example, drones, sensor networks, and the use of global positioning system-guided tractors, enable precise irrigation and fertilization, which are crucial in efficient resource use, water usage in critical areas where there is water scarcity, and minimizing the environmental impact of farming systems [29, 30].

4. Case studies of successful applications of climate-smart practices in rice farming

4.1 Global case studies of climate-smart agriculture in rice farming

Climate-smart practices have been successfully applied in rice systems globally with measurable benefits such as environmental sustainability, improved productivity, and resource efficiency.

4.1.1 China: Emission reduction strategies

In northern China, climate-smart agriculture practices have been widely adopted to address issues such as soil degradation, water scarcity, and rising temperatures [31]. The country has implemented conservation tillage and crop residue retention that have proven effective in reducing soil erosion and improving moisture conservation, particularly in northern regions [32]. Additionally, China has invested heavily in precision agriculture technologies, including drip irrigation and sensor-based farming, to optimize water use in arid areas [32].

Furthermore, in Hainan Province, China, emission reduction strategies, specifically the adoption of drought-tolerant rice varieties and optimized water management, were evaluated for their impact on greenhouse gas (GHG) emissions and rice yields. Two strategies, drought-tolerant variety with reduced nitrogen fertilizer (SR1) and SR1 plus plastic film mulching (SR2), reduced GHG emissions by 97 and 92%, respectively, compared to conventional practices. Importantly, while SR1 led to a 21% yield reduction, SR2 maintained yields comparable to traditional methods and quadrupled economic benefits, showing that climate-smart agriculture can simultaneously address climate mitigation and economic goals when carefully tailored to local contexts [33].

The impact of integrated rice-duck farming (IRDF) systems in the reduction of methane emissions from rice paddies, as well as the provision of natural control, has led to its popularity [34]. This agroecological approach involves the simultaneous cultivation of rice and ducks in paddy fields, creating a mutually beneficial ecosystem. The ducks serve multiple functions: They control pests by consuming insects and weeds, their paddling activity oxygenates the water and stimulates rice root growth, and their manure provides natural fertilization [35].

Adaptive and mitigatory climate-smart agriculture practices were implemented on a particular rice farm in Hubei, China, which led to a significant increase in rice yield (15.9%), and consequently, the farmers experienced an increase in their net income (19.3%). These synergies were especially effective during extreme weather events, highlighting the value of integrated approaches for both productivity and climate resilience [16]. In Heilongjiang, the use of side-deep fertilization has led to the enhancement of nitrogen use efficiency by 32–43%, and a decrease in nitrogen surplus and ammonia emissions, contrasting traditional methods [36].

4.1.2 India: Development of climate-resilient rice varieties

In India, implementing reduced or zero tillage with residue retention, combined with site-specific nutrient management and smart tools, increased rice system productivity by 10.5% and profitability by 29.4%, while saving 39.3% of irrigation water and boosting energy-use efficiency by up to 61% compared to conventional practices in the region [18, 37]. Techniques like the system of rice intensification and alternate wetting and drying achieved a 54.8% higher climate-smartness index than traditional continuous flooding and significantly reduced greenhouse gas emissions [21, 38]. Furthermore, zero-till direct-seeded rice with residue retention, followed by pulses or oilseeds, improved soil structure and increased soil carbon by over 70%, supporting long-term sustainability [23].

4.1.3 Indonesia: Regenerative technologies

In Indonesia, it is reported that innovative regenerative technologies can enhance resilience in salinity-stressed rice fields and promote net-zero farming practices, promoting food security and environmental sustainability [39].

The country also focuses on climate-smart agricultural practices that enhance the sustainability of its rice production systems, which are vulnerable to climate variability [40]. The system of rice intensification has been widely promoted, as it increases yields while reducing water usage and greenhouse gas emissions [41, 42]. Another key practice is alternate wetting and drying, which reduces methane emissions from rice fields by allowing periodic drying [40]. However, the widespread adoption of these practices is hindered by limited access to credit and extension services for small-scale farmers, particularly in remote areas [41].

4.1.4 Bangladesh: Adoption of saline-tolerant rice varieties

Bangladesh, one of the most climate-vulnerable countries, has pioneered innovative CSA techniques to cope with frequent floods, salinity intrusion, and extreme weather events. In coastal Bangladesh, some saline-tolerant rice varieties were developed to address soil salinity issues exacerbated by climate change. The adoption of these varieties such as such as BRRI dhan97 and BRRI dhan99 by farmers resulted in increased yields and improved livelihoods for smallholder farmers [43].

Traditional floating gardens, known as Baira cultivation, have been revived and adapted to grow vegetables in waterlogged areas, providing a sustainable livelihood option for communities in flood-prone regions [44]. Solar-powered irrigation systems have also been introduced to reduce reliance on fossil fuels and lower energy costs [45].

4.1.5 Southeast Asia: Reducing methane emissions through alternate wetting and drying and system of rice intensification

In Vietnam, alternate wetting and drying improves water productivity, requiring less water to produce rice and helping farmers in the region adapt to decreasing water availability and increased drought risk [46]. The newly developed submergence-tolerant rice variety Bangladesh Rice Research Institute (BRRI) dhan79 has shown a notable improvement in rice production in regions of Bangladesh prone to flash flooding, ultimately leading to enhanced food security and improved socioeconomic status of the farmers [24, 47]. Training programs, such as farmers' field schools, are central to climate-smart village approaches and have been implemented in Southeast Asia, specifically Cambodia, Laos, Myanmar, Vietnam, and the Philippines. These initiatives provide hands-on education in improved crop and pest management, participatory variety selection, and climate risk mapping, helping farmers adapt to climate variability and extremes [48].

4.2 Climate-smart agriculture in Africa: Continental case studies

In West Africa, drought-tolerant crop varieties and water-saving technologies have the potential to address water challenges and promote sustainable agricultural water management [49]. Some countries on the continent, including Nigeria, have also adopted climate-smart agriculture practices.

4.2.1 Madagascar: Implementation of the system of rice intensification

Madagascar has successfully implemented the System of Rice Intensification, leading to increased rice yields and reduced water usage. This approach has enhanced food security and resilience among smallholder farmers [50, 51].

4.2.2 Ghana: Climate-smart agriculture investment plan

Ghana's climate-smart agriculture investment plan focuses on promoting climate-smart agriculture technologies to increase productivity and enhance resilience. The plan emphasizes the adoption of improved seed varieties and sustainable farming practices [52, 53].

4.2.3 Senegal: Partnerships to promote climate-resilient agriculture

Senegal, in partnership with international organizations, has initiated programs to promote climate-resilient agriculture. These initiatives aim to improve rice production and support rural entrepreneurship among the smallholder farmers [54]. These farmers that are supported by government and non-governmental organizations programs have adopted various climate-smart agriculture practices such as using certified seeds, short-cycle crops, intercropping with legumes, agroforestry, composting, and organic pest control like Neem. Water is managed with stone bunds, and good farming methods like mulching and fire control are promoted [55].

4.3 Nigeria: Local case studies of climate-smart agriculture in rice farming

The use of different adaptation practices, such as early planting, improved seeds, and irrigation, has led to a substantial increase in yield and profits [56]. In North-Central Nigeria, extension services play a crucial role in disseminating climate-smart agriculture practices among rice farmers. However, challenges such as limited resources and training hinder effective adoption [57]. In Kebbi State, initiatives to adapt rice farming practices to climate change include the introduction of improved seed varieties and sustainable water management techniques [58, 59]. Also, in Ebonyi State, it was reported that farmers' perceptions of climate change and their uptake of climate-smart agriculture practices show a growing awareness and gradual implementation of climate-resilient farming methods [60].

5. Monitoring, evaluating, and scaling climate-smart agriculture in rice production

Monitoring, evaluating, and scaling climate-smart agriculture in rice production are crucial for enhancing productivity, boosting resilience, and preserving environmental sustainability amidst climate change impacts. Climate-smartness is often measured using indicators such as greenhouse gas intensity, water productivity, and a climate-smartness index (CSI). Process-based models such as denitrification-decomposition (DNDC) simulate yields, emissions, and water use to assess the effectiveness of irrigation strategies and their sensitivity to climate variables [19]. Data on methane emissions and rice yields are collected through automated chambers and weather stations, allowing for the evaluation of the trade-offs between productivity and emissions under varying weather conditions [61]. The benefits of climate-smart agricultural practices are evaluated through farmer surveys and statistical analyses, taking into account selection bias to ensure accurate evaluation of climate-smart agriculture's effects on perceptions, adoption rates, and economic outcomes [62, 63].

Common challenges in scaling climate-smart agriculture are institutional and capacity gaps, equity and inclusion, and context-specific barriers. Effective scaling depends on robust partnerships, capacity building, and integration of climate data and impact models into program design. Systemic change and long-term investment are necessary for sustainable scaling [64]. Also, scaling climate-smart agriculture requires understanding local farming systems, socioeconomic factors, and biophysical conditions. Insufficient extension services, land limitations, and high input costs hinder adoption [63, 65]. Other factors, including gender roles, access to training, resources, and youth engagement, have an impact influence adoption and scaling, necessitating targeted interventions to facilitate broad participation [66].

6. Policy and institutional support

Governments, non-governmental organizations (NGOs), and research institutions each play distinct but complementary functions in promoting climate-smart agricultural practices in rice production, spanning policy development and funding to community engagement and technology innovation. It is the responsibility of the government to establish policies that make climate-smart agricultural practices more feasible, encourage these practices through subsidies and carbon trading systems, and incorporate climate-smart agriculture into national strategies [67, 68]. The government provides functional extension and advisory services, which are essential for increasing awareness, training farmers, and promoting behavioral change toward climate-smart agricultural practices in rice production [69, 70]. Furthermore, establishing regulatory frameworks, such as land tenure and investment plans, is vital for upscaling climate-smart agriculture and ensuring sustained adoption over the long term [71].

Non-governmental organizations (NGOs) play a vital role in grassroots mobilization, awareness campaigns, and advocacy efforts, often reaching communities that government programs may overlook or fail to target [72]. They design their interventions to meet the specific needs of the local areas, such as promoting specific crops or sustainable practices. Climate-smart agricultural projects are often spearheaded and implemented by them, sometimes focusing on niche areas and integrating climate-smart agriculture into broader development programs like food security and women's empowerment schemes, while also fostering collaboration among relevant stakeholders [68, 73].

Research institutions develop new climate-smart agriculture technologies, generate evidence for best practices, and support capacity building—the outcomes of their work will guide policy, extension programs, and the incorporation and adaptation of climate-smart agriculture to local contexts [68, 74].

7. Conclusion

This literature revealed the significance of adopting climate-smart agricultural practices for sustainable rice production. With the global population rising rapidly and food needs escalating, it is essential to adopt measures that will strike a balance in food production. Based on the findings of the above literature, rice remains a key component in achieving food security. To achieve this, some of the climate-smart agricultural practices should be integrated into rice production, including water management techniques, soil health management, the use of resilient rice varieties, digital tools, and precision farming. It is essential to closely monitor, evaluate, and scale up these practices for optimal production. However, existing gaps encompass institutional and capacity gaps, as well as equity and inclusion issues, and context-specific barriers. The government, non-governmental organizations, and research institutions all play a vital role in promoting climate-smart agricultural practices. Therefore, addressing the current gaps and leveraging each sector's strengths will accelerate climate-smart agriculture adoption and impact, especially in rice production.

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