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REVIEW ARTICLE

Impact of climate change on rice crop yield: challenges and solutions

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Abstract

Rice is a staple food for billions of people worldwide, yet its production is increasingly threatened by the impacts of climate change. Rising temperatures, irregular precipitation patterns, increased salt and increasing frequency of extreme weather events significantly compromise both rice yield and grain quality. Key stressors such as heat induced spikelet sterility, drought-induced reduction in tillering and grain filling, salt stress inhibiting plant growth and flooding during critical growth stages pose serious challenges to productivity. Moreover, altered climatic conditions promote pest and disease outbreaks, exacerbate soil degradation, accelerate nitrogen loss and lead to salinity build-up further diminishing agricultural output. Smallholder farmers face socioeconomic vulnerability due to limited resources, inadequate technological access and insufficient adaptive capacity. Enhancing resilience involves innovations like establishing climate-resilient rice cultivars using sophisticated breeding procedures to improve tolerance to heat, drought, flooding and salinity challenges. Precision agriculture technologies (remote sensing, drones) optimize inputs through data-driven decisions. Sustainable approaches including alternate wetting/drying, direct-seeded rice and the System of Rice Intensification, conserve water. Climate-smart farming incorporating conservation agriculture, integrated crop-livestock systems and agroforestry increases overall resilience. Facilitating smallholders' access to climate information services, finance, insurance and capacity building is vital for boosting adaptive capacity. A coordinated, multi-pronged approach incorporating research, technical solutions, policy assistance and community engagement is necessary to create resilient rice farming systems capable of withstanding climate change impacts while maintaining food security.

Keywords: climate variability; decision support system; sustainable production; yield reduction

Introduction

Approximately 3 billion people worldwide consume rice, making it the most widely consumed staple food globally. Research indicates that rice serves as a primary food source for a larger population in comparison to any other crop (1). Asia produces and consumes 90 % of the world's rice and in many of these nations, irrigated and rainfed rice ecosystems from the backbone of food security. The projected population in Asia is anticipated to reach a figure of 5.2 billion by the year 2050, posing a significant challenge in meeting the demands for food and ensuring food security in the region (2, 3). Global food security is seriously threatened by climate change, which is having a negative impact on agricultural systems all over the world. Rainfall levels in rice-producing regions range from more than 5000 mm per year in Myanmar's Arakan Coast to under 100 mm per year in Al Hasa Oasis, Saudi Arabia; the average temperature during the rice cultivation period varies from 33 °C in Sindh, Pakistan, to 17 °C in northern Japan and rice can be grown from sea level up to 2600 m on the terraces of Nepal and Bhutan (4). Rice can be grown in various ways, from highly mechanized, irrigated, single summer cropping in countries like Italy, Japan, the U.S., Australia and Brazil, to rainfed rice systems in Latin America, sub-Saharan Africa and South and Southeast Asia; in rotation with other crops such as the vast rice/wheat systems of India and China and intensive, irrigated triple cropping in Indonesia and Vietnam (4).

However, the stability and productivity of rice production systems are under threat from the increasing impacts of climate change, which include changed patterns of precipitation, rising temperatures and an increase in the frequency of extreme weather events (5). While flooded rice production is associated with significant methane emissions, it can offer certain environmental benefits compared to other agricultural systems, such as reduced soil erosion and the potential for maintaining or even increasing soil organic matter. However, these advantages must be weighed against the high water demand and greenhouse gas emissions, making its overall sustainability context-dependent and subject to management practices (6). Natural disasters severely affect agricultural productivity and economic development in Asia. Typhoons, floods, droughts and infestations cut down technical efficiency in rice cultivation, with the most significant impact being from droughts (7). Over the past several decades, there has been an escalation in both the frequency and severity of tropical cyclones in the Pacific region. The South Asian population includes 262 million malnourished individuals, positioning it as the most food-insecure area globally (8). The rice-wheat cropping system, a common cropping practice meeting Asia's food requirements by half, is in immediate danger due to the impact of climate change (9).

This paper discusses the effects of climate change on rice crop productivity, farmers' issues and suggests new solutions to improve the resilience of rice farming systems to changes in weather patterns. Amidst these climate disruptions, rice farmers experience a range of problems in sustaining and enhancing agricultural productivity. Small-scale farmers, who constitute a large proportion of rice farmers in most countries, are especially exposed to the adverse effects of climate variability due to constraints in resource access, technological innovation and resilience capacity (10). Through a discussion of the interaction between climate change, rice production and agricultural adaptation strategies, this review aims to enhance understanding of the intricate dynamics that determine the future of global rice security.

Climate change effects on rice production

Climate change is having a significant impact on rice production globally, presenting challenges to both food security and the sustainability of agriculture. The impacts of climate change on the cultivation of rice involve a range of factors that affect both the quantity and quality of rice grains. Future agriculture and food systems must be enhanced to effectively address various abiotic and biotic pressures to mitigate the direct and indirect impacts of an evolving climate. In this context, highly managed agricultural systems like rice cultivation characterized by controlled water regimes, precision nutrient management, integrated pest management and the adoption of climate-resilient crop varieties present numerous opportunities to adapt to anticipated climate variations (11, 12). The changing climate is expected to exacerbate a range of challenges for rice crops, including heat, drought, salinity and flooding. Enhancing resilience to these environmental stresses has always been a focal point for research institutions like the International Rice Research Institute (IRRI), which focuses on agricultural practices in challenging conditions. Increasing CO_2 concentration in the atmosphere has a positive effect on crop biomass production, but its net effect on rice yield depends on possible yield reductions associated with increasing temperature. For every 75 ppm increase in CO_2 concentration, rice yields will increase by 0.5 t ha^{-1}, but yield will decrease by 0.6 t ha^{-1} for every 1 °C increase in temperature (13).

The following Fig. 1 illustrates world rice production trends (in million tonnes) vs. world temperature anomalies (in degrees Celsius) from 2014 to 2023. The paddy rice production figures, provided by FAOSTAT, denote the total annual yield of paddy rice globally, while the temperature anomalies denote NOAA/Berkeley Earth observations, which show departures from the long-term average global temperature. It's shows that, although rice production has overall seen an increase or stability over the last ten years, there are notable fluctuations in some years that coincide with increased global temperatures. For example, years with greater temperature fluctuations, like 2016, 2020 and 2023 tend to show declining rates of growth or small declines in rice production, indicating potential pressure on farm yields related to environmental conditions.

Green solid line

Represents the annual rice production globally, measured in million tonnes. Red dashed line: Indicates the global temperature anomaly (°C) relative to long-term averages.

This connection emphasizes the vulnerability of rice development to climate change-induced temperature variation, which can affect critical developmental stages like flowering and grain filling. While enhanced farming techniques and technology may have mitigated some negative impacts, the evidence underscores the growing need for climate-resilient rice varieties and targeted adaptation strategies to maintain global food security under evolving climatic conditions. Notable examples include drought-tolerant varieties such as IR64-Drought and Sahbhagi Dhan and submergence-tolerant varieties like Swarna Sub1 and IR64-Sub1, which have shown improved performance under stress conditions. Furthermore, climate variability has the potential to disturb indigenous predators of agricultural pests, resulting in disruptions within ecological systems and exacerbating pest infestations (14).

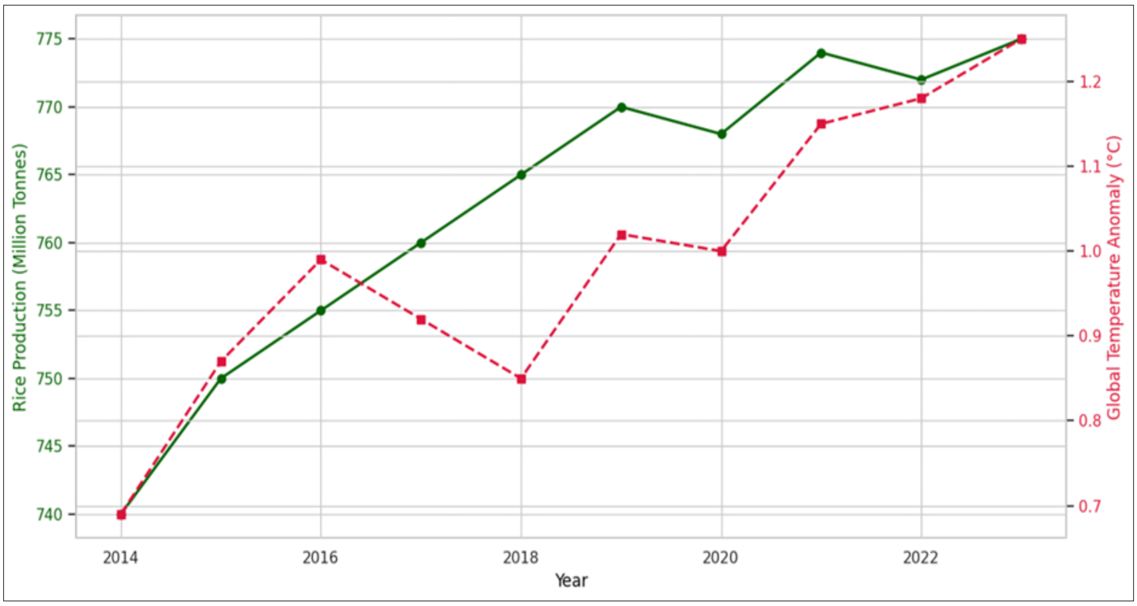

Fig. 1. Climate change effects on global rice production (2014-2023).

Factors influencing rice crop yield

As the effects of climate change become increasingly apparent, the resilience of agricultural systems, especially staple foods like rice (*Oryza sativa* L.), is being increasingly tested. Faced with changing climatic conditions, an array of factors exerts significant influence on the output of rice fields. These include biophysical properties such as temperature and rainfall, as well as socioeconomic forces such as market forces and agricultural policies. Grasping the intricate interplay among these elements is essential for formulating comprehensive approaches to uphold rice production in the face of a shifting climate (15).

Fig. 2. illustrates the estimated percentage reduction in global rice yield attributed to five major environmental stresses: temperature, drought, salinity, heavy rainfall and flooding. These estimates cover the period from 2014 to 2024. Of these stresses, flooding consistently had the highest potential for yield loss, with estimated effects of 20 % in 2014 to over 55 % in 2024, consistent with evidence that flooding can reduce rice yields by up to 80 % during extreme events (16). Drought also has a clear increasing trend, from 12 % to 26 %, consistent with its increasing frequency and severity globally (17). Salinity stress remains a major factor, with an estimated 25 % yield loss by 2024, consistent with reports of up to nearly 30 % reductions in salinity areas (18).

By comparison, temperature impacts demonstrate a moderate but consistent trend, consistent with the gradual increase in mean growing-season temperatures, with research estimating potential yield loss over 10 % from heat stress (19). In the meantime, intense rain, though moderately variable, constitutes an increasingly severe threat as heavy precipitation events increase in frequency, with possible yield loss up to 17 % in 2024 (20).

Temperature and humidity

Temperature and humidity are important environmental variables that have significant impacts on rice growth, development and yield. In climate change, knowledge on how temperature and humidity impact the production of rice is imperative to the development of efficient adaptation strategies. This thorough analysis will examine the complex relationship between temperature, humidity and rice production. Temperature plays a crucial role in shaping various physiological processes in rice plants. High temperatures can have detrimental effects on rice growth and development, leading to reduced yields and poor grain quality. Extreme temperatures, particularly in the range of 32 to 36 °C, accompanied by changing relative humidity levels, have been found to greatly enhance spikelet sterility in rice, eventually downgrading grain formation and resultant yield potential (21). Moreover, higher temperatures negatively affect rice grain yield, with studies highlighting strong relationships between increased mean minimum temperatures and yield reductions (22).

Temperature and CO_2 interaction

Although elevated CO_2 levels have the potential to enhance photosynthesis and yield in C_3 crops like rice, particularly under optimal conditions, this benefit is context-dependent and may be offset by other stress factors. Independently, CO_2 also plays a significant role in the greenhouse effect by capturing short-wave radiation emitted from the Earth's surface and re-radiating it, thereby contributing to the increase in global surface temperatures. The potential increase in biomass production resulting from elevated CO_2levels could lead to higher yields, assuming that key processes such as microsporogenesis, flowering and grain-filling remain unaffected by environmental factors like drought or high temperatures. From a biochemical perspective, the increase in CO_2 concentration prompts a rise in RuBisCO levels while suppressing photorespiration. Consequently, a moderate increase in temperature may enhance net photosynthesis and CO_2 absorption in rice, particularly when daytime temperatures remain within the optimal range of 25-32 °C. However, temperatures exceeding critical thresholds such as 35 °C during flowering can significantly reduce spikelet fertility, impair grain filling and ultimately lower yields (23). Furthermore, rice grains play a significant role as a storage site for assimilates and any disruption or limitation of this carbon sink would hinder the exploitation of the benefits associated with elevated CO_2 levels due to a lack of responsiveness in photosynthesis (24).

High night temperature

Research indicates how temperature trends influence rice yields. From their data, they found that during this time, the average annual highest temperature had increased by 0.35 °C for the maximum and by a more significant 1.13 °C for the minimum. Interestingly, they noted a 10 % decrease in grain yield for each 1 °C increase in minimum temperature during the dry season, while maximum temperature had no appreciable impact on

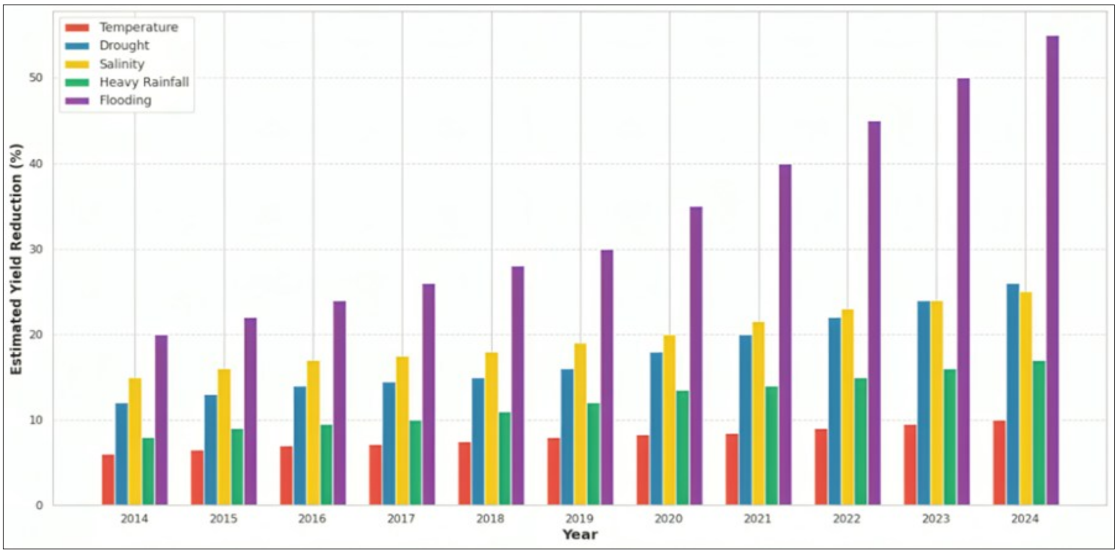

Fig. 2. Year-wise impact of environmental factors on global rice yield (2014-2024).

yield (22). Research highlights that high day and night temperatures shortened the grain growth period, but growth was slower at the early to middle stages of grain filling. They also indicated a reduction in cell size halfway between the centre and endosperm surface under high night temperatures (22/34 °C) relative to high day temperatures (34/22 °C). In spite of these findings, the precise effects of high night temperatures on rice yield are still inadequately investigated and need more attention, especially considering forecast night-time warming patterns (25).

Drought

The IPCC Technical Paper on Climate Change and Water affirmed with a high level of certainty that the adverse consequences of future climate change on freshwater systems are anticipated to surpass the advantages (26). Compared to the current situation, a large increase in regions where water stress exacerbation is predicted, whereas only a small percentage of areas will see an improvement in water stress conditions. Even with an increased overall water supply, the impacts of increased precipitation variability, changes in seasonal runoff patterns, water quality problems and flood risks are likely to have a strong impact on food production.

A shortage of water when compared to normal circumstances is considered drought (27). The Godavari River Basin's six districts, comprising 11 % of the region classified as very vulnerable, saw a sharp decline in rice production, which accounted for 41.02 % of the total production loss during the worst-case drought event (28). Drought definitions are contingent upon the disciplinary viewpoint, encompassing meteorological, hydrological and agricultural standpoints. The occurrence of agricultural drought transpires when the soil lacks adequate moisture to fulfil the water needs of crops, consequently leading to diminished yields. The manifestation of catastrophic, chronic, or intrinsic drought stress is contingent upon the timing, duration and intensity of the phenomenon, necessitating distinct coping strategies, adaptive measures and breeding goals. Given that it impacted 300 million people and 55 % of the nation's land, the 2002 Indian drought might be considered a catastrophic occurrence. Compared to the inter-annual baseline trend, rice production fell by 20 % (29). Furthermore, drought-induced physiological stresses exacerbate production losses by weakening plant defences and making them more vulnerable to pests, illnesses and other biotic stresses (30).

Research indicates that climate change has significantly impacted global crop production in recent decades. Research indicates that estimated mean yield reductions of 8 % for major crops in Africa and South Asia are expected by the 2050s (31). However, suggests that wheat and maize yields may increase in colder regions due to elevated CO_2 levels, while rice yields are expected to decrease globally due to water scarcity (32). The worldwide distribution of drought risk, as depicted in Fig. 3, emphasizes the differential levels of vulnerability in different areas. Moldova, Ukraine, Bangladesh, India and Serbia are recognized to have the greatest drought risk, with their exposure determined by past drought severity, water stress, population density and agricultural dependence. The map breaks down drought risk into five categories, from low to high, with large sections of Asia, Europe and South America classified as medium to high-risk. This data is highly applicable to the research on microplastic pollution in aquatic ecosystems, as drought can enhance microplastic concentration in freshwater systems because of lower water availability and flow. This interaction can further exacerbate food security in very drought-prone agricultural areas like India and Bangladesh. It can impact water quality and soil conditions as well. Moreover, extended drought can also affect the transport and deposition of microplastics in aquatic environments, changing their pattern and ecological role. It is imperative to understand these linkages to formulate integrated climate adaptation and pollution abatement plans, especially for areas experiencing dual threats of both drought and environmental pollutants.

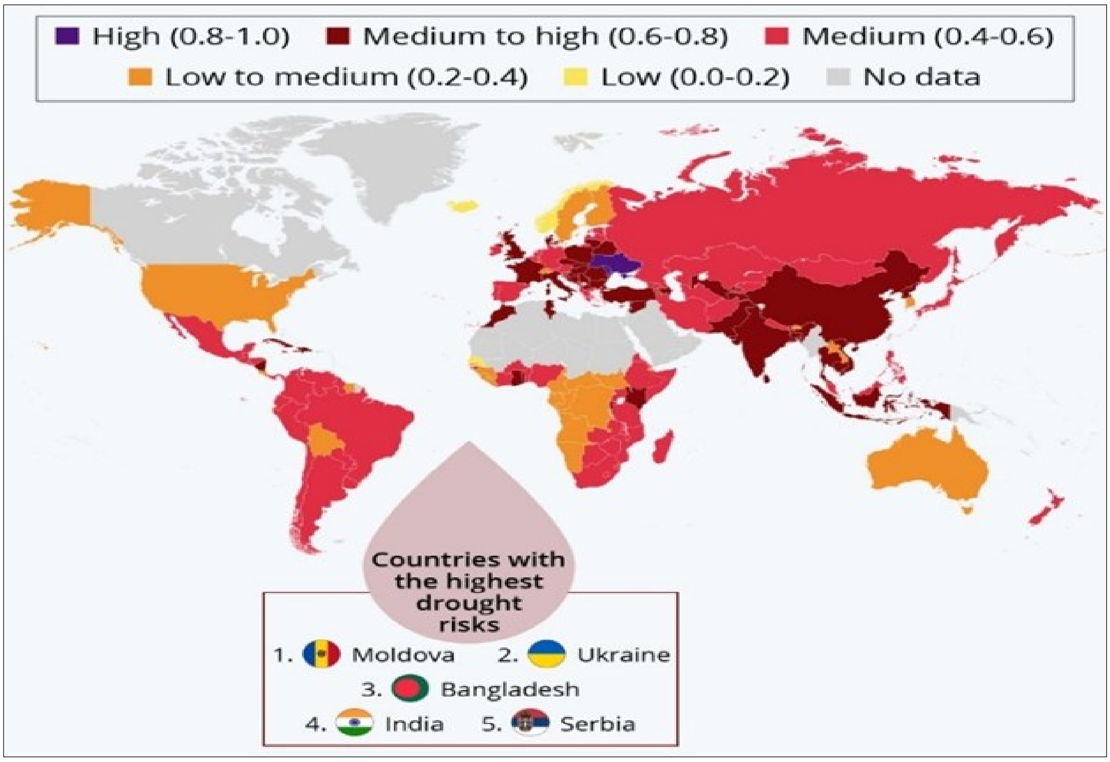

Fig. 3. The world map of drought risk (2019). [source: Statista]

Salinity

Climate change is producing unprecedented changes in global habitat salinity, which is posing severe risks to coastal ecosystems and human activity. The projected increase in sea level and alteration of river flow regimes are expected to elevate estuarine water salinity levels, which are potentially harmful to plants and animals, upsetting fish and bird habitats and reducing important ecosystem services (33). For Bangladesh, climate-driven changes in sea level, temperature, rainfall and river flows are predicted to increase river salinity significantly by 2050, leading to freshwater deficits, agricultural issues and changes in aquatic ecosystems (34). Global mean sea level is projected to rise by approximately 0.29 to 1.1 m by 2100, depending on future greenhouse gas emissions scenarios. This rise is driven by a combination of thermal expansion of seawater and the melting of glaciers and polar ice sheets. Rising sea levels are expected to increase coastal salinity, which can adversely affect rice yields, even in regions that were previously considered suitable for cultivation (35).

Research indicates that increasing soil salinity presents a major challenge to the cultivation of high-yielding variety (HYV) rice in the coastal regions of Bangladesh, with a projected yield loss of 15.6 % in areas with salinity of more than 4 dS/m by the year 2050. Barisal and Chittagong districts have been estimated to lose 7.7 % and 5.6 %, respectively. Salinity affects rice yield through several mechanisms, including osmotic stress, floret sterility and delayed flowering. Osmotic stress, caused by high salt concentrations in the soil, reduces the plant's ability to absorb water, leading to cellular dehydration and impaired physiological processes such as photosynthesis and nutrient uptake. This results in stunted growth, poor tillering and lower biomass accumulation. These effects are particularly pronounced in the southwestern coastal region, where sea-level rise and freshwater scarcity exacerbate soil salinity and further threaten rice production. The authors urge that the potential of salt-tolerant rice varieties such as BRRI Dhan 47 and BINA Dhan 10, while emphasizing the necessity for integrated adaptation practices involving better water management and climate-resilient policies to offset projected future yield loss (36).

Heavy rainfall and flooding

As climate zones shift and water availability increases from dry to wet regions, extreme precipitation and flooding become more frequent. Global assessments by organizations such as the Food and Agriculture Organization (FAO) suggest that climate change will cause both positive and negative shifts in food production potential, depending on the region, crop type and adaptive measures in place. The seasonal cycle of water availability is associated with an increase in the intensity of extreme precipitation and floods. Increased severe precipitation combined with the anticipated decline in overall precipitation in mostly arid Middle East regions, such as Northern Saudi Arabia and the Levant, but precipitation will also increase in about half of the area(37).

Because of the increasing temperatures and less precipitation during planting seasons, it is anticipated that crop water requirements will increase. It suggests that crop productivity in South Africa's Olifants basin may decrease by as much as 65 % by the century's end. Future agricultural productivity will be increased by using rainwater harvesting, complete irrigation and adjusting planting dates in light of climate change(38). A 10 % decrease in the amount of land used for growing rice that receives rain is possible. The effects on rice yields under rain-fed conditions can vary widely, ranging from a 35 % decrease to a 5 % increase, with the north-eastern area being the most vulnerable (39). Rainfall is predicted to increase by 4.5 % between 2013 and 2033 and by 6 % between 2033 and 2053, with implications for Rwanda's key agricultural goods. Unpredictable rainfall patterns and the shifting of rainy seasons may cause late planting and low harvests (40).

Challenges faced by rice farmers due to climate change

Temperature extremes and heat stress

The growth of rice is faced with severe challenges from heat stress, which negatively impacts growth, yield and quality at all developmental stages as depicted in Fig. 4. The reproductive stage is highly vulnerable to injury, as heat causes pollen abortion and reduced seed-setting percentages. To overcome these issues, researchers are exploring multiple strategies. These involve breeding for heat-tolerant varieties using advanced genetic approaches like marker-assisted selection, cultivar selection for desirable traits like early morning flowering and enhanced anther size, Notable efforts include the development of 'N22' and 'IR64' rice lines by the International Rice Research Institute (IRRI**)** and national breeding programs in South and Southeast Asia, which are incorporating these traits to improve resilience under rising temperatures and application of agronomic strategies like modification of planting times and optimal water management (41, 42, 43). Additionally, the application of plant growth regulators and exogenous treatments such as salicylic acid, proline, glycine betaine and ascorbic acid can enhance the antioxidant capacity of rice plants, helping to mitigate oxidative stress and reduce yield losses under adverse climatic conditions (43, 44). Integration of these approaches is essential for the generation of stress-tolerant rice varieties and the provision of food security under climate change.

Table 1. Impacts of altered precipitation patterns on rice and mitigation strategies (44-46)

Climate stressor	Impacts on rice production	Adaptive strategies	References
Prolonged droughts	Reduced tillering, impaired grain formation and yield losses, especially in rainfed systems	Development of drought-tolerant rice varieties, adjustment of crop calendars and the use of short-duration crop varieties.	(44, 45)
Excessive rainfall	Flooding and waterlogging can lead to root and seedling damage, ultimately inhibiting the overall growth of rice plants.	Breeding flood-tolerant varieties and enhancing drainage can help counter flooding impacts.	(44, 45)
Irregular monsoon and extreme events	Frequent dry and wet spells disrupt sowing and harvesting cycles.	Rescheduling planting dates and using weather forecasting tools can reduce disruptions from erratic weather.	(45)
Water scarcity in arid/ semi-arid areas	Increased pressure on marginal lands leads to reduced crop productivity.	Promoting less water-intensive crops and adopting weather-linked insurance can help sustain productivity under climate stress.	(46)

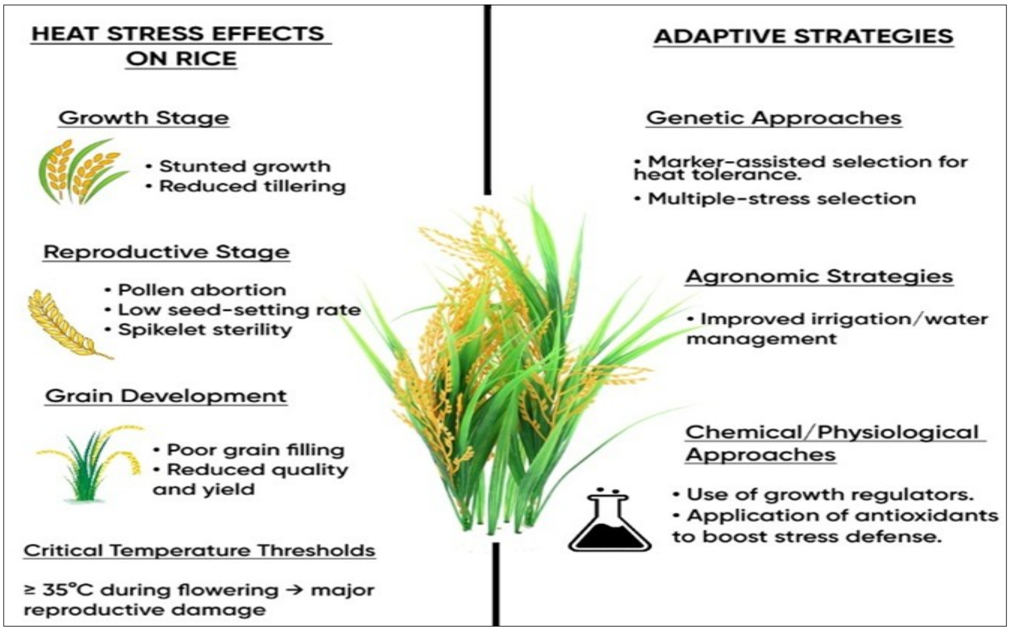

Fig. 4. Temperature and heat stress in rice.

Altered precipitation patterns and water scarcity

Table 1 illustrates that changes in precipitation patterns, particularly in the form of prolonged droughts and excessive rainfall, pose significant challenges to rice farmers, especially those reliant on rainfed agriculture. These changes can inhibit plant growth, reduce tillering, impair grain formation and lead to yield losses. The impact of these changes is further exacerbated by the increasing trend in monsoon rainfall and the prevalence of frequent dry and wet periods. Stress-tolerant rice varieties and rescheduling of crop calendars have been suggested as potential mitigation strategies. Climate change is also expected to reduce agricultural production and put further pressure on marginal land, particularly in arid and semi-arid regions. Therefore, there is a need to emphasize the use and production of food crops that can withstand these changes, as well as to implement strategies such as short-duration crops and weather-linked agricultural insurance.

Pest outbreaks and disease incidences

Climate change contributes significantly to increased pest and disease pressure on rice farming systems by creating favourable conditions for pest development, altering pest behaviour and weakening plant defenses (Table 2). For instance, higher temperatures and humidity can accelerate the life cycles of major rice pests such as the brown planthopper (*Nilaparvata lugens*), rice stem borers (*Scirpophaga incertulas*) and facilitate the spread of diseases like rice blast and bacterial leaf blight, hence more infestations and losses; also, the efficacy of management measures affects the extent to which climate change affects crop productivity and land use, emphasizing the international collaboration and concerted plant protection policies required to counter the widening host range and geographical distribution of pests.

Soil degradation and nutrient depletion

Both soil deterioration and nutrient depletion are made worse by climate change, which poses a severe threat to rice farming systems (57). Essential nutrients such as nitrogen, phosphorus, potassium and micronutrients like zinc and iron are often lost due to increased soil erosion, leaching from intense rainfall and reduced organic matter content under changing climatic conditions. This is particularly concerning in countries like India and Pakistan, where rice cultivation is a crucial component of the agricultural economy (58). The impact of climate change on rice production can be minimized through the implementation of climate-resilient agricultural technology, such as enhanced water and fertilizer management (59). To address the multifaceted issues that climate change presents to rice cultivation, however, additional research and legislative action are required.

As shown in Fig. 5. depicts the principal effects of climate-driven soil degradation, in order of severity. One of the most severe impacts is food insecurity, which is the result of decreased soil fertility and decreased crop yield. Soil erosion of the nutrient-rich topsoil, spurred on by violent weather patterns, washes away the upper part of the soil necessary for plant growth. Leaching of nutrients and damaged uptake due to enhanced rainfall and soil imbalance also drains essential minerals. Loss of organic content and microbial life diminishes soil strength and derails nutrient cycling, while lower carbon sequestration leads to elevated atmospheric CO_2 concentrations. Furthermore,

Table 2. Examples of likely effects of climate change on plant pests (insects, pathogens and weeds) in different climate zones 2050-2100 (48-56)

Climate Zone	Likely effects of climate change on future pest risk (mainly 2050-2100)	References
Arctic	Pest risks are expected to rise in tundra regions.	(48)
Boreal	Higher risks of insect and plant diseases, particularly in boreal forests.	(49)
Temperate	Agriculture and forestry in temperate zones will likely face more insect pest challenges. Diseases may also increase, especially in Western Europe. Weeds are expected to become more problematic and there will be a shift and expansion of pest ranges northward.	(50, 51, 52, 53)
Subtropical	Southern Europe and similar regions may see greater saturation of pest risk in agriculture and forestry, with diseases increasing in prevalence. Pest ranges are expected to expand.	(54)
Tropical	Insect pests may face temperatures above their optimal survival range, potentially lowering their populations. However, disease risks show mixed trends; some studies suggest decreases, while others highlight rising risks based on specific local factors.	(55, 56)

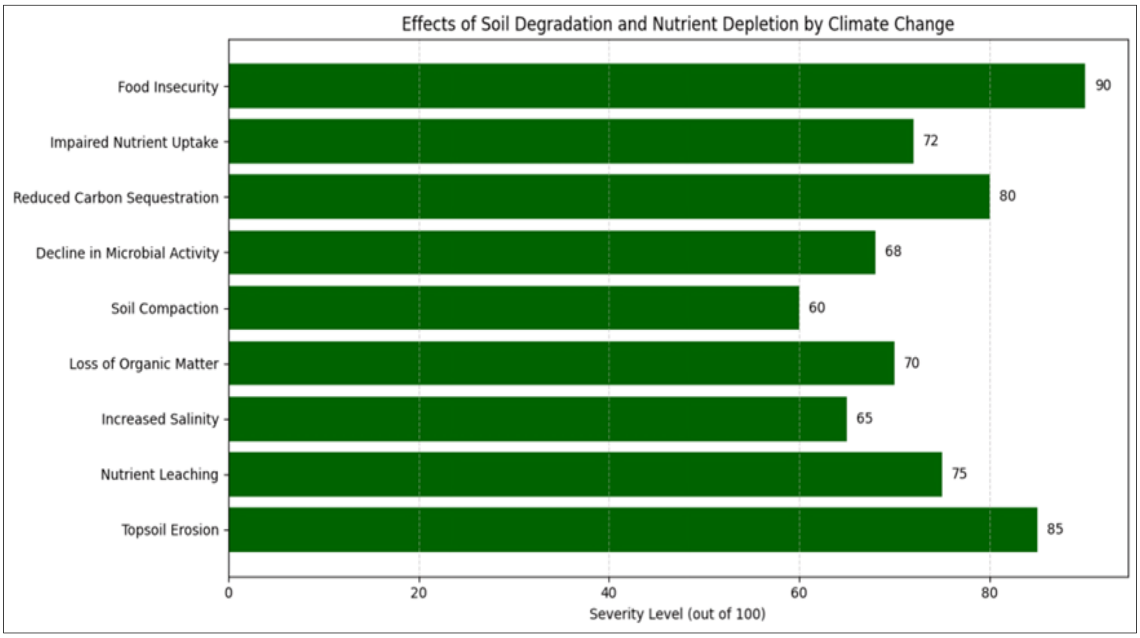

Fig. 5. Effects of soil degradation and nutrient depletion by climate change.

climate change causes salinity and compaction, which render soils more uninhabitable for crops. Altogether, these impacts highlight how climate-caused soil degradation inherently jeopardizes agricultural sustainability and food security.

Socioeconomic vulnerability and livelihood risks

Smallholder rice farmers, who constitute a substantial share of rice producers, are highly sensitive to the impacts of climate change due to low resources, technological access and adaptive capacity (60, 61). This susceptibility is worsened by climate-related shocks, which prolong cycles of poverty and vulnerability and disrupt market dynamics, influencing commodity prices and market access. The absence of access to financial services, insurance programs and support systems further compounds the risks faced by these farmers. Urgent intervention measures are needed to expand communication networks, give subsidies and training and create chances for income diversification. Technical, financial and institutional support is also vital to boost agricultural production and food security(62, 63).

Innovations and technological solutions for climate-resilient rice farming

The influence of climate change on rice production is a growing concern, with possible ramifications for global food security and livelihoods (64). However, there is potential for innovation and technical solutions to strengthen the resilience of rice agricultural systems (65). Agroecological strategies, such as diversification of agroecosystems, can increase the resilience of farmers and rural communities (64). Climate-resilient agriculture demands the incorporation of land degradation processes into adaptation planning, increased knowledge exchange and creative management and policy choices (65). The multifunctionality of agriculture, access to diversity, capacity building and continuity of effort are critical elements of innovation systems that might boost food security in the face of climate change (66). Adaptation methods, including changes in land and cropping practices, the creation of new crop varieties and changes in food consumption and waste, are critical for agricultural adaptation to climate change (67).

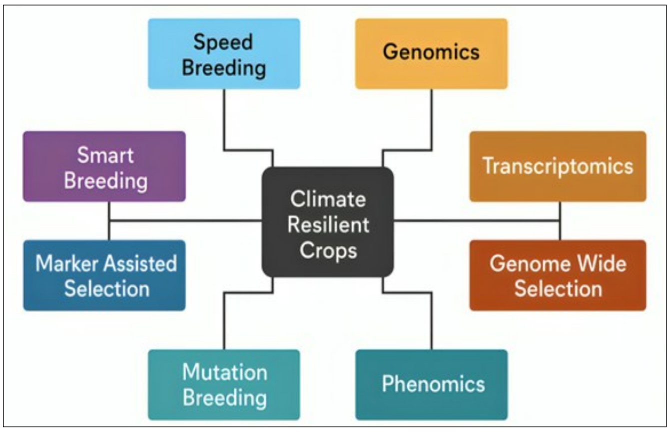

Fig. 6. Modern breeding approaches for developing climate resilient crops (81).

Climate-resilient rice varieties

In order to create rice varieties that are more adaptable to climate change, both conventional breeding methods and cutting-edge biotechnological techniques are being employed, with an emphasis on improving tolerance to heat, drought, flooding and salinity. Techniques such as CRISPR-Cas9 genome editing and marker-assisted selection are being used to precisely modify or select for stress-resistance traits in rice (68) as depicted in Fig. 6. Research indicates that these cultivars have enhanced yield stability and productivity even in challenging environmental circumstances (69). In order to ensure that locally adapted varieties are relevant and adopted in a variety of agro-ecological situations, farmer participation in the selection and promotion of these varieties is essential (68). Furthermore, by enhancing root systems and soil biota, the system of rice intensification (SRI) is an agroecological technique that increases the resilience of rice crops to climate change (70).

Precision agriculture technologies

Making educated decisions is made possible by real-time data on crop health, soil moisture and pest infestations provided by precision agricultural technology like as satellite photography, drones and remote sensing (72). These technologies optimize resource utilization and reduce environmental consequences, in conjunction with sensor-based irrigation systems and variable rate application technologies (73). Additionally, they are essential in enhancing nutrient management and utilization effectiveness, which lessens environmental issues (74). Moreover, precision agriculture enables farmers to tailor inputs such as fertilizers and pesticides more precisely to the needs of specific areas within their fields. This optimizes resource use, reduces environmental impact and enhances resilience to climate change. By applying inputs only where and when needed, farmers can minimize waste and ensure that crops receive the nutrients and protection they require, even in the face of shifting environmental conditions (75). In addition, the data collected through precision agriculture systems can be used to improve crop breeding programs, developing varieties that are better adapted to the challenges posed by climate change, such as heat and drought tolerance (76). The following Table 3 implies the importance and application of precision farming across various fields.

Sustainable water management practices

Sustainable water management techniques, such as alternate wetting and drying (AWD), direct-seeded rice (DSR) and system of rice intensification (SRI), can help alleviate the water scarcity in rice farming, which is made worse by climate change (89, 90, 91). These methods preserve or increase yields while promoting water efficiency and conservation. To reduce water use without sacrificing production, AWD, for instance, entails regularly drying and re-flooding rice fields. Similarly, SRI encourages rice farming with less water and chemical inputs, focusing on soil health and root development, whereas DSR reduces the requirement for water -intensive nursery setups (92). The urgent issue of water scarcity in rice growing can be greatly helped by these approaches.

Climate information services and decision support tools

Research indicates that it is critical to address farmers' information needs on climate change and facilitate their access to and comprehension of this data (93, 94). While research highlights the importance of integrating climate information into an institutional structure that incorporates community-level response (95). The necessity for scalable innovations in creating locally relevant climate information (93). The importance of climate information in affecting farming decisions and the necessity for better access to high-quality climate data (96, 97). Together, these studies show that climate information services play a key role in helping farmers anticipate and prepare for the challenges that come with climate change.

Climate-smart farming practices

Climate-smart agriculture (CSA) is a multifaceted approach that addresses the impacts of climate change on agriculture while promoting sustainability and resilience. It encompasses a range of methodologies, including conservation agriculture, agroforestry and efficient irrigation practices (98, 99). The Venn diagram (Fig. 7) illustrates what Climate Smart Agriculture (CSA) is actually all about: it combines three large ideas: adapting to a changing climate, minimizing its impact and ensuring everyone has a full plate to eat. For starters, CSA assists farmers by helping them adapt through ways to deal with the likes of unseasonable weather, floods, or droughts, whether by employing drought-tolerant crops or improved water-saving methods. And then there's mitigation, which involves reducing the greenhouse

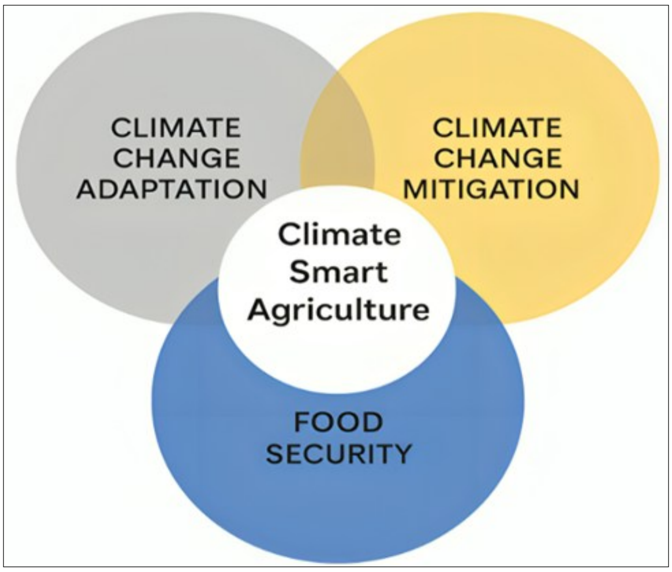

Fig. 7. Three components of climate-smart agriculture.

Table 3. Application of precision farming across various fields (77-88)

Sr. No	Key functions	How it helps	Measurable benefits	Problems it addresses	References
1	Improving soil health	Uses modern technology to boost soil quality and make better use of resources	Soil quality improves by 20-30 % and resource efficiency increases by 15 %	Poor soil fertility and inefficient resource use	(77, 78)
2	Saving water	Uses sensors and data to manage irrigation more effectively	Water use drops by 30-50 % and crop yields rise by 10-20 %	Water shortages and ineffective irrigation methods	(79, 80)
3	Real-time crop monitoring	Uses drones, satellite images and sensors to keep track of crop health	Yields increase by 10-25 % and input costs drop by 15 %	Lack of timely crop data and high production costs	(81, 82)
4	Managing nutrients	Helps farmers apply fertilizers where they're needed most based-on data	Nutrient use becomes 20 % more efficient and fertilizer costs are reduced by 25 %	Overuse of fertilizers and high nutrient expenses	(83)
5	Controlling Pests and Diseases	Uses data and remote sensing to detect problems early	Pest and disease impact is lowered by 20-40 %, reducing crop losses by 15-25 %	Frequent pest and disease outbreaks	(84, 85)
6	Optimizing Planting and Harvesting	Uses GPS-guided machinery and data analysis for more efficient operations	Crop yields increase by 15-30 % and fuel use drops by 10-20 %	Inefficient planting/harvesting and high fuel costs	(77, 86)
7	Adapting to Climate Change	Uses climate data and predictive models to prepare for weather changes	Crop resilience improves by 20 % and adaptation costs fall by 10 %	Negative effects of climate change and high adaptation expenses	(81, 87)
8	Sustainable land management	Helps manage land more carefully to reduce environmental damage	Land degradation is reduced by 20 % and overall efficiency improves by 15 %	Mismanaged land and environmental degradation	(77)
9	Reducing carbon and energy use	Optimizes input use to lower both carbon emissions and energy costs	Carbon emissions decrease by 15-25 % and energy use drops by 10-20 %	High carbon footprints and high energy expenses	(81, 88)

gases that farming emits, such as using cleaner practices or planting carbon-absorbing trees. And of course, food security is important. CSA benefits farmers by enabling them to produce enough food, earn a fair income and feed their neighbours. Where these three objectives intersect is where CSA excels. It's a wiser, more sustainable method of farming that benefits people and the planet alike, today and tomorrow. Adoption of CSA has seen encouraging outcomes in the form of higher crop yields, more efficient use of water and greater economic returns for farmers (99). Nevertheless, several challenges restrict large-scale adoption, including financial limitations, knowledge and policy-related issues. Addressing these challenges requires designing inclusive education schemes, supportive policy frameworks and enhanced coordination between stakeholders (100). Incorporating digital advancements, including Internet of Things (IoT)-based precision agriculture, provides additional avenues for improving CSA practice. For example, IoT-enabled soil moisture sensors help optimize irrigation scheduling, automated weather stations provide real-time climate data for adaptive planning and remote pest detection systems allow for timely and targeted pest management. Ongoing research and innovative activity are essential for driving the large-scale adoption of CSA and for the establishment of resilient and sustainable agriculture systems (101).

Future Directions

The development of rice cultivars that are adaptable to climate change is imperative, as climate variability poses a substantial threat to global rice production. To enhance rice tolerance to various stresses, researchers have highlighted the importance of genetic improvement and advanced breeding techniques, such as marker-assisted selection and gene editing To enhance rice tolerance to various stresses, researchers have highlighted the importance of genetic improvement and advanced breeding techniques, such as marker-assisted selection and gene editing (102, 68). These strategies are especially important in places that are prone to drought and receive rain, as there is a significant demand for rice types that can withstand drought. In order to prevent rice yield losses and fluctuations, there is a necessity for particular adaptation techniques, including improved production practices. But it's crucial to remember that any effects of climate change on rice ecosystems should also be taken into account. These effects could include variations in temperature, UV-B radiation and CO_2 levels (59).

It is commonly acknowledged that digital agriculture and big data analytics have the ability to improve the productivity and resilience of rice farming systems (102, 103). These technologies, which enable data-driven decision-making and resource optimization, include remote sensing, unmanned aerial vehicles (UAVs) and satellite images. They provide real-time data on crop health, soil moisture levels and insect infestations (103). Large-scale datasets can be further analysed using machine learning algorithms and predictive analytics to spot patterns, trends and possible hazards. This information can then be used to develop adaptive management plans and lessen the effects of climatic variability on rice yields (104). However, the effective implementation of these digital tools requires considerable physical infrastructure, skilled human resources and robust data governance frameworks (103). In order to ensure sustainability and foster resilience, it is imperative that rice farming communities address the socio-economic aspects of climate change. Farmers can be shielded from climate-related shocks and losses via creative financing methods, insurance plans and risk-sharing agreements (105). To enable farmers to adapt to climate change and diversify their income streams, capacity-building projects, farmer education programs and extension services are crucial. Rice farming communities are vulnerable to market integration and climate change, but are more resilient with enhanced market access and value chain linkages. Given the critical role of climate in rice cultivation, it is necessary to adopt climate-resilient varieties and intelligent farming practices to safeguard future productivity (11). The possible pathways to address these challenges and ensure sustainable rice farming are summarized in (Fig. 8).

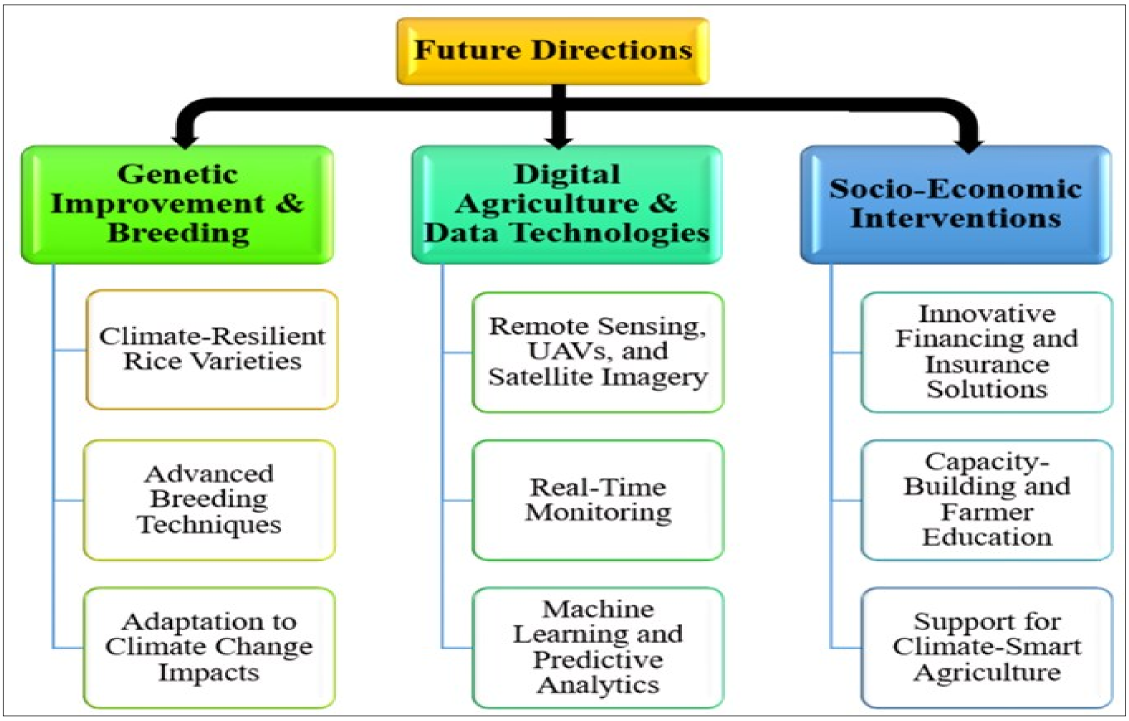

Fig. 8. Future directions for rice farming.

Conclusion

Climate change poses a significant threat to global rice production and food security, as rising temperatures, changing precipitation patterns, increased salt and more frequent extreme weather events contribute to declining yields and quality. Addressing these challenges requires a multi-pronged approach. This includes the development of climate-resilient rice cultivars through breeding and biotechnology, which can enhance tolerance to diverse environmental stresses. It also involves the deployment of precision agriculture technology like remote sensing and decision support systems for improved resource use and data-driven decision-making. Implementing sustainable water management strategies such as alternate wetting and drying, direct-seeded rice and the system of rice intensification can preserve water resources while maintaining or increasing yields. Adopting climate-smart farming methods, including conservation agriculture, integrated farming systems and agroforestry, helps increase resilience and lessen the consequences of climate change. Moreover, providing smallholder farmers with access to climate information, funding, insurance and capacity-building initiatives is crucial to boost their adaptive capacity and reduce socioeconomic vulnerability. A concerted effort encompassing multidisciplinary research, technical improvements, governmental support and community engagement is vital to create resilient rice farming systems and ensure global food security amidst climate change.

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Authors' contributions

AA conceptualized the study, developed the methodology, performed the formal analysis, led the investigation and wrote sections of the original draft. KR co-conceptualized the study, contributed to methodology design, assisted in formal analysis and critically revised the manuscript. TT conducted the investigation, contributed to the original draft and assisted in supervision. SP supervised the study and provided critical review and editorial input. RJ contributed to supervision, manuscript review and structural editing. GD provided supervision, reviewed the manuscript and gave final editorial refinements. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they do not have any conflict of interest.

Ethical issues: None

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