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Recent Advances in Rice Improvement- innovations and Impacts on Yield and Sustainability: A Review

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ABSTRACT

Rice (*Oryza sativa* L.), a semi-aquatic annual grass native to tropical Asia, holds the distinction of being the world's most crucial food crop, serving as a staple for over a third of the global population. In many regions, particularly in Asia, it is deeply woven into cultural traditions, religious practices, culinary habits and economic frameworks. Asia accounts for more than 90% of the world's rice production and consumption, providing 60% of the caloric intake for 3 billion people in the region. Global food security is greatly influenced by rice, which is a staple food for more than half of the world's population. In order to satisfy the demands of a growing population and changing climate, recent improvements in rice enhancement have concentrated on improving yield, stress toleranceand nutritional quality. The production of high-yielding and stress-tolerant varieties by conventional breeding and biotechnological techniques including marker-assisted selection, genomic selectionand CRISPR-Cas9 gene editing are among the major advancements in rice breeding that are highlighted in this article. Additionally, the integration of precision agriculture and digital farming techniques has revolutionized rice cultivation, optimized resource use and minimizing environmental impact. We have discussed the challenges faced in the implementation of these technologies and the future prospects for sustainable rice production. These advancements not only promise to boost productivity but also contribute to the resilience and sustainability of rice farming systems, ensuring food security for future generations.

Key words: CRISPR-Cas9, Food security, Genome editing, Marker-assisted selection, Rice, Rice improvement, Stress tolerance, Sustainability.

Rice (*Oryza sativa* L.) is one of the most important cereal crops, providing a primary source of calories for over half of the global population (Khush, 2013). Asia accounts for more than 90% of the world's rice production and consumption, providing 60% of the caloric intake for 3 billion people in the region (Bajpai and Singh, 2010). The increasing demand for rice, driven by population growth and dietary shifts, necessitates continuous improvement in rice yield, qualityand stress tolerance. Traditional breeding techniques have played a significant role in rice improvement over the past century; however, the rate of yield gains has slowed, necessitating the adoption of advanced technologies (Fukushima *et al*., 2020). The intra-specific variation in rice is vast, making sub-specific classification crucial for rice breeders and geneticists. As one of the primary centers of rice cultivation, India boasts the largest rice harvesting area globally. In terms of production, India ranks second after China and holds the same position in rice exports, following Thailand among the leading rice-exporting nations (Singh and Singh, 2008).

Recent developments in molecular biology and genomics have revolutionized rice breeding. Marker-assisted selection (MAS) and genomic selection (GS) have enabled the identification and utilization of genes associated with desirable traits, accelerating the breeding process (Wang *et al*., 2019). The advent of CRISPR-Cas9 gene editing technology has further expanded the potential for precise genetic modifications, allowing for the targeted improvement of rice traits such as disease resistance, drought tolerance and grain quality (Zhang *et al*., 2021).

In addition to genetic advancements, the integration of precision agriculture and digital farming techniques have transformed rice cultivation practices. The use of remote sensing, drone technology and data analytics allows for precise monitoring and management of rice fields, optimizing resource use and reducing environmental impacts (Yang *et al*., 2017). These innovations are critical for enhancing the sustainability of rice production systems and addressing the challenges posed by climate change and resource limitations.

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Despite these advancements, several challenges remain in the widespread adoption and implementation of new technologies in rice improvement. Issues such as regulatory hurdles, intellectual property rights and the need for capacity building among farmers and breeders must be addressed to fully realize the potential of these innovations (Qaim, 2020).

This review aims to provide a comprehensive overview of the recent advances in rice improvement, focusing on the innovations in breeding and cultivation practices. The challenges and future prospects for sustainable rice production in the context of global food security are discussed in this paper (Fig 1: Growth stages of rice, from germination to harvest, highlighting key phenological phases).

Need for improvement

The growing global population and the challenges posed by climate change necessitate continuous improvements in rice yield, quality and stress tolerance. While traditional breeding techniques have achieved considerable successes, the demand for higher productivity and resilience against biotic and abiotic stresses requires the integration of advanced technologies (Fukushima *et al*., 2020). The integration of advanced technologies is essential for addressing the evolving demands in rice production. Genomic selection, for instance, allows breeders to make more informed decisions by leveraging genetic information, thereby accelerating the development of high-yielding and resilient rice varieties (Heffner *et al*., 2010). Additionally, biotechnological approaches such as gene editing (*e.g*., CRISPR/Cas9) enable precise modifications in rice genomes, facilitating the introduction of traits like drought tolerance and disease resistance (Zhang *et al*., 2018).

Incorporating these advanced technologies into rice breeding and production systems not only increases productivity but also contributes to sustainable agricultural practices by reducing input costs and minimizing environmental impacts (Fujita *et al*., 2021). The combined use of traditional breeding methods and modern technologies offers a holistic approach to meet the growing challenges in rice production while ensuring food security for future generations.

Advances in rice breeding

Conventional breeding techniques

These breeding methods have been instrumental in enhancing rice yields and developing new varieties. These methods involve the selection and crossbreeding of high-performing varieties to introduce desirable traits. However, these processes are often time-consuming and labor-intensive (Wang *et al*., 2019).

Molecular breeding approaches

Molecular breeding approaches have revolutionized traditional plant breeding by incorporating advanced genetic tools to accelerate and improve the precision of crop improvement. These techniques enable the identification and manipulation of specific genes associated with desirable traits, leading to the development of superior rice varieties. Two prominent methods in molecular breeding are Marker-Assisted Selection and Genomic Selection (Varshney *et al*., 2021).

a. Marker-assisted selection (MAS)

MAS is a breeding strategy that assists in selection by using molecular markers associated with particular genetic features. This method significantly speeds up the breeding cycle and enhances the accuracy of selecting plants with desired characteristics. Molecular markers can be DNA sequences that are closely associated with the genes controlling important traits such as yield, disease resistance and stress tolerance (Collard and Mackill, 2008).

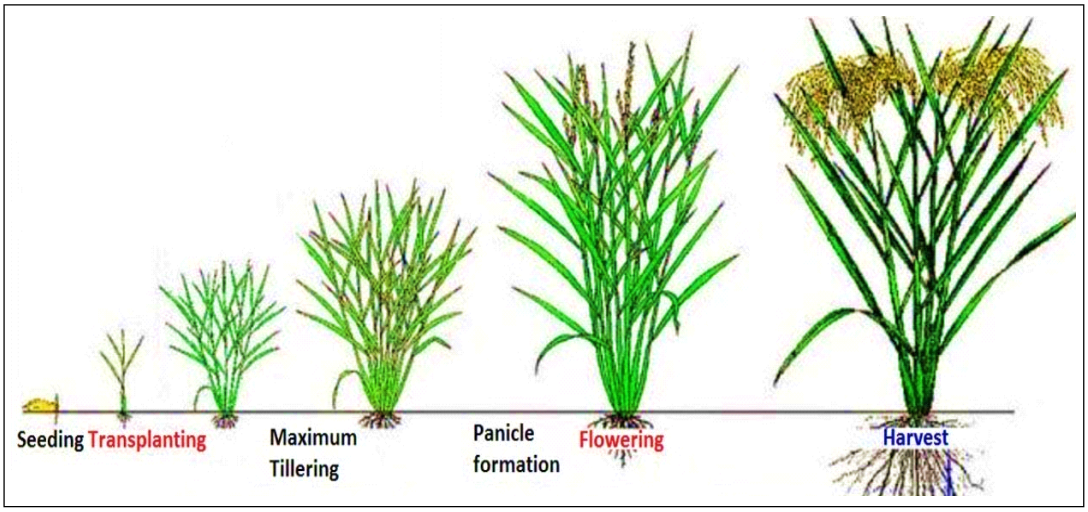


Fig 1: Different growth stages of rice.

By enabling breeders to more accurately and efficiently choose plants containing desired genes, MAS has completely modified rice breeding strategies. Through the application of molecular markers associated with particular features, this approach facilitates the quick production of varieties that have enhanced stress tolerance, grain qualityand resistance to disease (Wang *et al*., 2019).

Applications in rice improvement

MAS has been widely applied in rice breeding to improve various traits:

- **Disease resistance:** MAS has facilitated the development of rice varieties with resistance to major diseases like bacterial blight and blast. For example, the introgression of the Xa21 gene using MAS has led to the creation of bacterial blight-resistant rice varieties (Huang *et al*., 1997).
- **Grain quality:** Enhancements in grain quality traits, such as amylose content and aroma, have been achieved using MAS. Molecular markers linked to these traits allow breeders to select for high-quality grain characteristics (Zeng *et al*., 2017).
- **Abiotic stress tolerance:** MAS has been instrumental in developing rice varieties that can withstand abiotic stresses. Rice production in rainfed environments, which account for around 45% of the global rice area, is constrained by various abiotic stresses. Key challenges include water deficit, submergence, salinity and deficiencies in phosphorus (P) and zinc (Zn) (Singh, 2013). such as drought, salinity and submergence. For instance, the Sub1A gene, associated with submergence tolerance, has been introduced into popular rice varieties through MAS (Xu *et al*., 2006).

Advantages and challenges

The major advantage of MAS is its ability to reduce the breeding cycle duration by allowing early selection of desirable traits. This method also enhances the precision of breeding programs, leading to more predictable outcomes. However, the success of MAS depends on the availability of reliable markers and the genetic complexity of the target traits (Collard and Mackill, 2008).

b. Genomic selection (GS)

Using genome-wide markers to forecast an individual's breeding value within a breeding population, genomic selection is an advanced breeding strategy. Unlike MAS, which targets specific markers, GS considers the entire genome, thereby capturing the effects of many genes simultaneously. This approach has been shown to accelerate genetic gains in breeding programs (Meuwissen *et al*., 2001). Genome-wide markers are used by GS to forecast breeding line performance, greatly improving selection speed and accuracy. This method has been particularly effective in accelerating genetic gains in rice breeding programs (Crossa *et al*., 2017).

Applications in rice improvement

GS has been successfully applied in various rice breeding programs:

- **Yield Improvement:** By using genome-wide markers, GS can predict the overall genetic potential of a plant for yield-related traits, leading to the selection of high-yielding varieties. Studies have demonstrated significant yield improvements in rice using GS (Spindel *et al*., 2015).
- **Complex trait enhancement:** GS is especially helpful for enhancing complex qualities like yield stability and stress tolerance that are controlled by several genes. The holistic approach of GS enables the capture of small effects from many loci, enhancing the overall genetic gain for these traits (Crossa *et al*., 2017).
- **Speed breeding:** GS can significantly reduce the breeding cycle duration by allowing the selection of superior genotypes early in the breeding process. This rapid selection process is crucial for meeting the growing demand for improved rice varieties (Varshney *et al*., 2021).

Advantages and challenges

The major advantage of GS is its ability to improve complex traits controlled by multiple genes, providing a more comprehensive approach to breeding. Additionally, GS can be integrated with speed breeding techniques to accelerate the development of new varieties. However, the implementation of GS requires substantial investments in genotyping and computational resources, which can be a barrier for some breeding programs (Crossa *et al*., 2017).

c. CRISPR-Cas9 and gene editing

CRISPR-Cas9 is a revolutionary gene-editing technology that has transformed genetic engineering by providing a precise and efficient method for making targeted modifications in the DNA of organisms. This technology is based on a natural defense mechanism found in bacteria, which use CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) and Cas (CRISPR-associated) proteins to protect against viral infections (Doudna and Charpentier, 2014). In recent years, CRISPR-Cas9 has become a powerful tool for improving crop varieties, including rice, by enabling precise alterations to the genome that enhance desirable traits and confer resistance to various stresses.

The mechanism of CRISPR-Cas9 involves two key components: A guide RNA that directs the Cas9 nuclease to the specific location in the DNA where the edit is to be made and the Cas9 enzyme that creates a double-strand break in the DNA. This break triggers the cell's natural repair mechanisms, which can be harnessed to introduce specific changes in the genetic code (Jiang *et al*., 2013).

Despite its advantages, the use of CRISPR-Cas9 in agriculture raises ethical and regulatory questions. As gene editing technologies continue to evolve, it is essential to establish clear guidelines to ensure the safety and

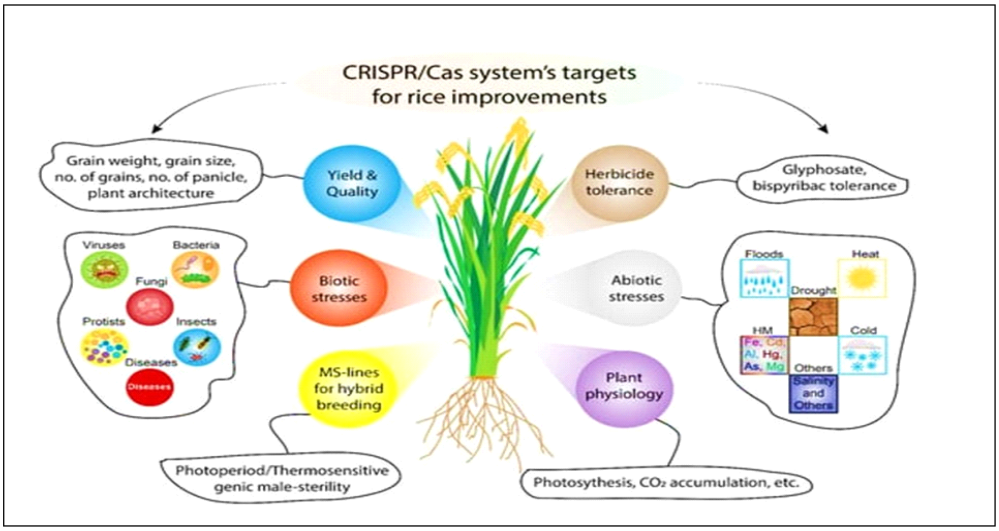


Fig 2: Potential CRISPR/Cas targets for rice crop improvement (Tabassum *et al*., 2021).

sustainability of genetically edited crops in food systems (Lusser *et al*., 2012). Fig 2 highlights potential CRISPR/ Cas targets for rice crop improvement include genes that negatively regulate yield, quality, stress toleranceand plant physiology. Developing male sterile (MS) lines for hybrid breeding can be achieved by targeting genes like the Thermo-sensitive Male Sterility 5gene. Additionally, genes related to heavy metal tolerance (*e.g*., Fe, Cd, Al, Hg, As, Mg) can be modified for enhanced stress resistance (Tabassum *et al*., 2021).

Applications in rice improvement

- **Applications in disease resistance:** The CRISPR-Cas9 system has been employed to develop rice varieties with enhanced resistance to major diseases. For example, targeted editing of the gene encoding for the rice blast resistance protein (Pi-ta) has led to the creation of rice varieties with improved resistance to the blast fungus, which causes significant yield losses (Liu *et al*., 2017). Similarly, the editing of genes associated with bacterial blight resistance, such as the Xa21 gene, has produced rice lines with enhanced resistance to this devastating pathogen (Li *et al*., 2020).
- **Applications in drought tolerance:** Drought is a critical challenge for rice production, especially in water-scarce regions. For centuries, farmers have selected plants that survived drought events, resulting in a rich genetic diversity among traditional cultivars in their response to water deficit (Singh, 2013). CRISPR-Cas9 has been used to edit genes involved in drought tolerance mechanisms. For instance, the OsDREB1A gene, which regulates drought-responsive pathways, has been targeted to enhance the drought resilience of rice plants (Kumar *et al*., 2017). Additionally, modifications in genes related to root architecture, such as the OsNAC10 gene, have improved drought tolerance by enhancing root growth and water uptake (Ooka *et al*., 2003).
- **Applications in grain quality:** Rice quality is a key factor, significantly influencing both market value and consumer acceptance. Grain quality is shaped by various aspects, including grain appearance, nutritional content and cooking and eating characteristics (Singh and Singh, 2012). CRISPR-Cas9 technology has also been applied to improve grain quality traits in rice. For example, editing the genes responsible for amylose content has allowed breeders to produce rice varieties with desired grain texture and cooking properties (Zhu *et al*., 2021). The precision of CRISPR-Cas9 enables targeted modifications to enhance specific quality traits without affecting other desirable characteristics, leading to improved grain quality and consumer acceptance (Wang *et al*., 2020). Fig 3 highlights the CRISPR-Cas mediated genome editing in rice for the improvement of different traits. This Fig 3 illustrates the diverse applications of CRISPR-Cas technology in enhancing various traits of rice. The genome-editing tool CRISPR-Cas allows precise modifications of rice DNA, enabling targeted improvements in agronomic, nutritional and resistance traits.

Advantages and challenges

CRISPR-Cas9 technology offers several significant advantages, including its precision, efficiency and versatility in gene editing. Its ability to target specific genomic sites enables the creation of rice varieties with precise traits, reducing the risk of unintended genetic alterations. This precision facilitates the development of crops with complex

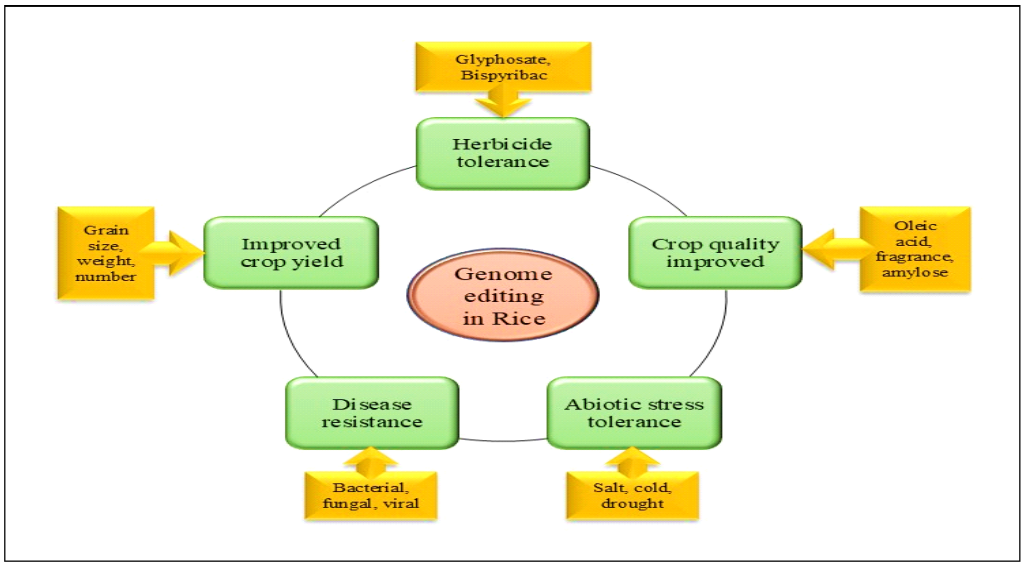


Fig 3: CRISPR-Cas mediated genome editing in rice for the improvement of different traits.

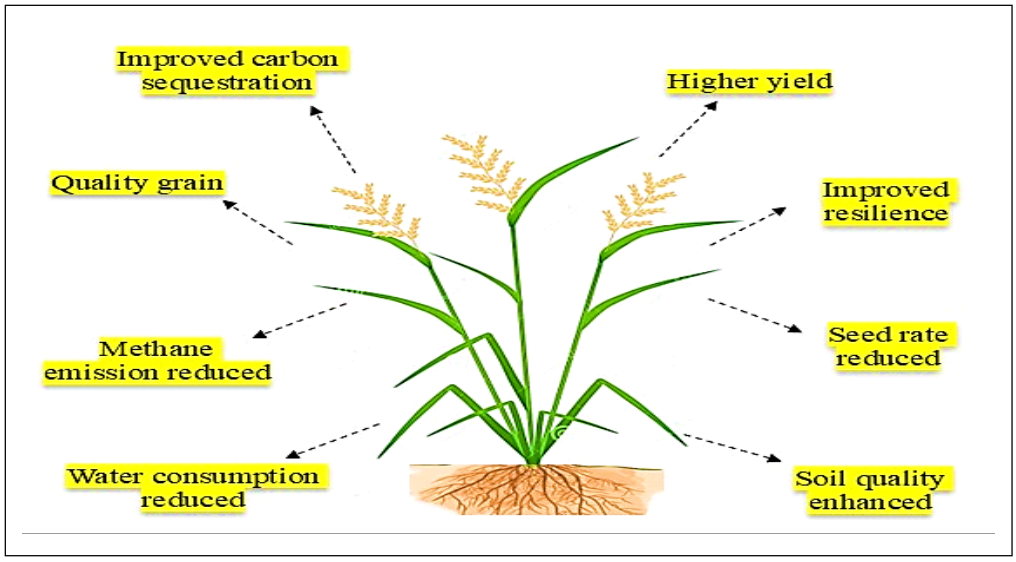


Fig 4: Tackling food security with cimate-smart rice.

trait improvements and allows for simultaneous editing of multiple genes. Additionally, CRISPR-Cas9's efficiency accelerates the breeding process, providing timely solutions to agricultural challenges. However, the technology also faces challenges, such as potential off-target effects, where unintended modifications might occur despite advancements in specificity. Furthermore, the regulatory landscape for gene-edited crops varies across regions, potentially impacting the adoption and commercialization of CRISPR-edited rice varieties. Ensuring robust safety and regulatory frameworks, along with continued research to minimize off-target effects, is crucial for the responsible application of CRISPR-Cas9 in crop improvement.

Innovations in rice cultivation

Fig 4 highlights the role of climate-smart rice in ensuring food security amid the growing challenges posed by climate change. Climate-smart rice varieties are specifically developed to sustain high productivity while mitigating the adverse effects of environmental stresses. Key aspects include.

i. Precision agriculture

Remote sensing technologies

Remote sensing technologies, such as satellite imagery and drones, provide valuable data on crop health, soil conditions and field variability. Satellite imagery offers comprehensive insights into large-scale field conditions,

while drones equipped with multispectral sensors can capture high-resolution data on crop health and stress levels (Yang *et al*., 2017). This data allows for precise monitoring and targeted interventions, enabling farmers to optimize resource use and improve overall crop management. In addition to monitoring crop health and soil conditions, remote sensing technologies facilitate early detection of pest infestations and diseases, which is crucial for timely intervention. By analyzing spectral reflectance data from both satellites and drones, farmers can identify stress signatures that indicate potential pest or disease issues before they become widespread. This proactive approach helps minimize crop losses and reduce the reliance on chemical treatments (Kumari *et al*., 2020).

Drone technology

Drones have revolutionized precision agriculture by offering real-time, aerial observations of rice fields. Equipped with various sensors, drones can assess plant health, detect pest infestations and monitor growth stages with high accuracy (Zhang *et al*., 2018). This capability allows for timely and precise application of inputs, such as fertilizers and pesticides, reducing waste and improving crop yields. Furthermore, drones facilitate the collection of valuable data on soil conditions and moisture levels, enabling farmers to make informed decisions regarding irrigation and resource management. By employing multispectral and thermal imaging, drones can provide insights into crop vigor and stress, helping farmers identify areas needing attention before problems escalate. This targeted approach not only enhances resource efficiency but also contributes to sustainable farming practices by minimizing the overuse of chemicals and promoting environmental stewardship (Gonzalez *et al*., 2020).

Data analytics

Data analytics integrates information from multiple sources, including remote sensing and field sensors, to provide actionable insights for rice management. By analyzing data on weather patterns, soil moisture and crop growth, data analytics tools help farmers make informed decisions about irrigation, fertilization and pest control (Wolfert *et al*., 2017). This approach enhances resource efficiency and supports the adoption of best management practices tailored to specific field conditions. Additionally, data analytics can facilitate the development of customized crop management plans by evaluating the unique characteristics of different fields. By segmenting fields based on factors such as soil type, topographyand historical yield data, farmers can implement site-specific practices that optimize resource use and enhance crop performance. This tailored approach is particularly beneficial in rice production, where variations in soil fertility and moisture levels can significantly impact yield outcomes (Liu *et al*., 2020).

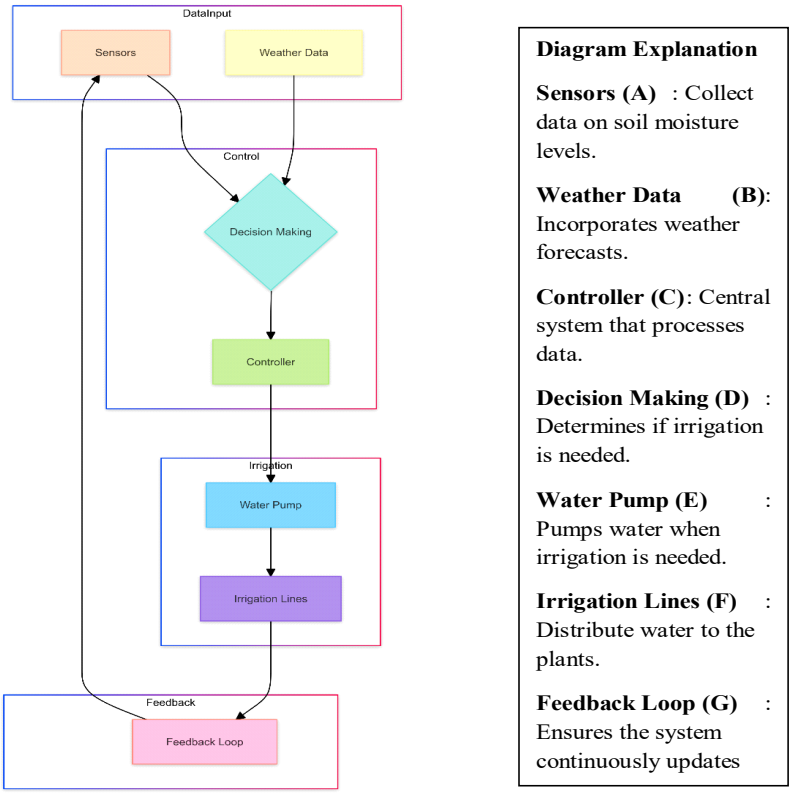


Fig 5: Flowchart of working principle of smart irrigations systems.

ii. Digital farming techniques

Smart irrigation systems

Smart irrigation systems use sensors and automated controls to optimize water use in rice cultivation. These systems monitor soil moisture levels and weather conditions to determine the precise amount of water needed, reducing water waste and ensuring crops receive adequate hydration (Chukalla *et al*., 2015). By improving water use efficiency, smart irrigation systems contribute to sustainable rice production and help to mitigate the impacts of water scarcity. This figure provides a detailed flowchart illustrating the operational framework of smart irrigation systems, designed to optimize water use efficiency while ensuring adequate irrigation for crops (Fig 5).

Automated monitoring systems

Automated monitoring systems provide continuous tracking of field conditions, including soil moisture, temperatureand crop health. These systems use sensors and IoT (Internet of Things) technology to collect real-time data, which is then analyzed to guide management decisions (Tsouros *et al*., 2019). Automated monitoring helps farmers detect issues early, such as nutrient deficiencies or pest infestations, allowing for prompt corrective actions. The figure illustrates the structure and functioning of an automated irrigation system, highlighting its key components and operational workflow. The system integrates advanced technologies to ensure precise and efficient water distribution (Fig 6).

iii. Advancements in crop management practices

Integrated pest management (IPM)

IPM combines biological, cultural and chemical control methods to manage pests in rice cultivation. Innovations in IPM include the use of biological control agents, such as predatory insects and parasitoids and the application of eco-friendly pesticides. IPM strategies aim to reduce pest populations while minimizing environmental impact and promoting sustainable farming practices (Ehler and Bottrell, 2000). In addition to biological control agents and eco-friendly pesticides, integrated pest management (IPM) also emphasizes the importance of cultural practices to enhance pest resistance and crop health. Crop rotation, intercropping and the use of resistant crop varieties are vital components of IPM strategies that disrupt pest life cycles and reduce the likelihood of infestations. For instance, rotating rice with legumes can improve soil health and disrupt pests that are specific to rice, thereby lowering pest pressures in subsequent rice crops (Naylor *et al*., 2021).

Nutrient management optimization

Optimizing nutrient management involves the precise application of nutrients based on soil testing and crop requirements. Technologies such as variable rate fertilization (VRF) allow for targeted application of nutrients, reducing excess and ensuring that crops receive the right amounts (Raun and Johnson, 1999). This approach improves nutrient use efficiency and minimizes environmental pollution from fertilizer runoff. In addition to variable rate fertilization (VRF), integrating technologies like soil moisture sensors and remote sensing can further enhance nutrient management strategies. These technologies provide real-time data on soil nutrient levels and crop health, enabling farmers to adjust fertilization practices based on current conditions rather than relying solely on pre-season assumptions. For example, soil moisture sensors can indicate when crops are experiencing stress, allowing farmers to synchronize irrigation and fertilization efforts, ensuring that nutrients are available precisely when plants need them (Zhang *et al*., 2021).

Climate-resilient practices

Adapting to climate change is a critical aspect of modern rice cultivation. Innovations in climate-resilient practices include the development of rice varieties that can withstand extreme weather conditions, such as floods and droughts. Additionally, practices such as conservation tillage and cover cropping help to enhance soil health and resilience to climate variability (Pathak *et al*., 2019). In addition to

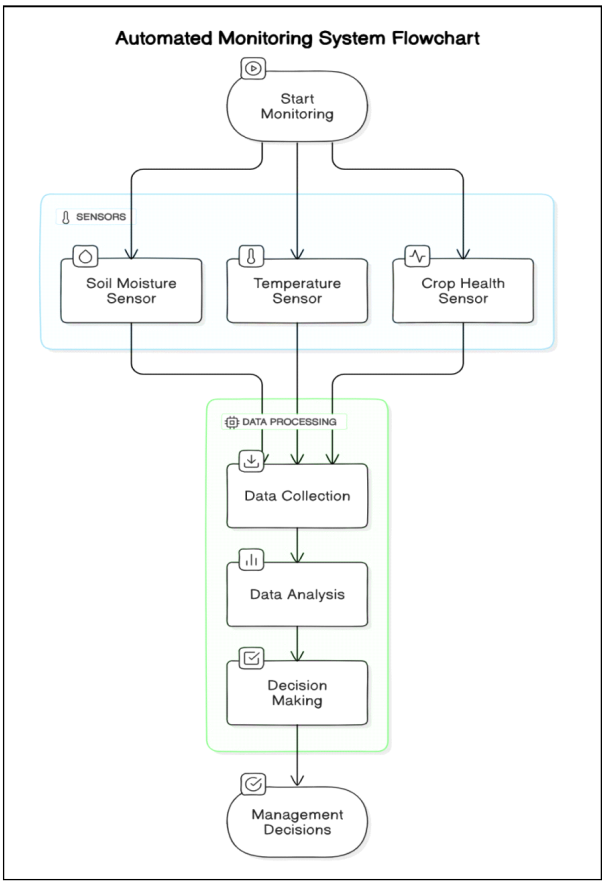


Fig 6: Diagrammatic representation of automated irrigation system.

varietal improvement, the adoption of agroecological practices plays a vital role in building climate resilience. Techniques such as agroforestry and intercropping not only improve biodiversity but also create microclimates that can buffer against extreme weather events. For example, integrating trees with rice systems can enhance soil moisture retention and reduce evaporation rates, which is particularly beneficial during drought conditions (Lal, 2020).

Challenges in rice improvement

Regulatory hurdles

The adoption of new technologies in rice improvement frequently encounters significant regulatory hurdles that can impede progress in agricultural innovation. These challenges include stringent approval processes and compliance with biosafety regulations, which are designed to ensure the safety of genetically modified organisms (GMOs) and new breeding techniques. While such regulations are essential for safeguarding human health and the environment, they can also create bottlenecks that delay the deployment of beneficial technologies to farmers, ultimately affecting food security and agricultural productivity (Qaim, 2020).

Recent research has highlighted that the lengthy and complex regulatory pathways often lead to increased costs and uncertainty for developers of new rice varieties, particularly those utilizing advanced biotechnology tools such as CRISPR-Cas9 and gene editing (Santos *et al*., 2021). These technologies have the potential to significantly enhance rice varieties' resilience to climate change and improve yield, yet the fear of regulatory backlash can discourage investment and innovation in this area (Lema *et al*., 2022). Moreover, the variability in regulatory frameworks across different countries complicates the process for developers seeking to commercialize new technologies globally (Lusser *et al*., 2014).

Intellectual property rights

Intellectual property rights (IPR) play a significant role in shaping the landscape of agricultural innovation, especially concerning advanced breeding technologies. In developing countries, the tension between protecting intellectual property and ensuring access to these technologies poses a critical challenge. Rao and Dev (2019) highlight that stringent IPR regimes can hinder the adoption of new breeding techniques, such as gene editing and biotechnology, which are essential for addressing food security and agricultural sustainability. This concern is echoed in more recent literature, which underscores the need for balanced policies that encourage innovation while facilitating access for smallholder farmers and local communities (Kumar *et al*., 2023).

For instance, a study by Mazzucato and Semieniuk (2023) emphasizes that overly restrictive IPR frameworks can exacerbate inequalities, limiting technological advancements to wealthier nations and large agri-businesses, while smaller players struggle to compete. To mitigate these issues, the implementation of alternative models, such as open-source breeding initiatives and collaborative partnerships, is suggested. These approaches can foster knowledge sharing and innovation while ensuring that local farmers benefit from advancements in breeding technologies (Jain *et al*., 2024). Ultimately, addressing IPR in the context of advanced breeding technologies requires a nuanced understanding of local needs and the broader implications for agricultural development in low-resource settings.

Capacity building for farmers and breeders

Effective implementation of advanced agricultural technologies is heavily reliant on capacity building among farmers and breeders. As noted by Krupnik *et al*. (2019), training and education are crucial to empower these stakeholders with the knowledge and skills required to leverage innovations such as precision agriculture, genetic engineering and sustainable farming practices. Recent studies further emphasize the importance of tailored training programs that address the specific needs and contexts of local farmers. For instance, a study by Galiè *et al*. (2023) highlights that hands-on training, combined with access to technological resources, significantly enhances farmers' confidence and ability to adopt new methods.

Moreover, collaboration between research institutions and agricultural extension services is vital for creating a supportive learning environment. Research by Faramarzi *et al*. (2024) underscores the effectiveness of participatory training approaches that involve farmers in the development and implementation of new technologies, ensuring that the solutions are relevant and practical. Additionally, the integration of digital tools in training programs can facilitate wider outreach and provide farmers with continuous support, as discussed by Aderinola *et al*. (2023). By focusing on comprehensive capacity-building initiatives, the agricultural sector can ensure that farmers and breeders are well-equipped to harness the full potential of advanced technologies, ultimately contributing to improved productivity and sustainability in food systems.

Future prospects for sustainable rice production

The future of sustainable rice production is pivotal in addressing global food security challenges while minimizing environmental impacts. As the world faces increasing population pressures, climate changeand resource constraints, innovative approaches and technologies will play a crucial role in shaping the rice sector's sustainability. Below are key prospects for the future of sustainable rice production.

Integrating advanced technologies

The integration of advanced breeding techniques and modern cultivation technologies holds great potential for improving rice production systems, making them more resilient, efficientand sustainable. This is critical as global demand for food continues to riseand environmental

pressures such as climate change, land degradation and water scarcity threaten agricultural productivity (Tilman *et al*., 2011). Advanced breeding methods, such as marker-assisted selection (MAS), genomic selection (GS) and CRISPR-Cas gene editing, allow breeders to accelerate the development of rice varieties with enhanced traits like abiotic stress tolerance, disease resistance and improved nutrient use efficiency (Jaganathan *et al*., 2018). These technologies enable precise and rapid introgression of desired traits, reducing the breeding cycle time and making it easier to adapt rice crops to changing environmental conditions.

Furthermore, integrating these breeding advances with innovative cultivation practices-such as precision agriculture, which uses data-driven tools like drones, sensors and AI to optimize resource use-can significantly improve rice yields and resource efficiency (Zhang *et al*., 2019). Techniques like the System of Rice Intensification (SRI), which reduces water usage and improves plant health, have also shown promise in increasing yields while reducing environmental impact (Uphoff, 2003).

By combining genetic improvements with sustainable farming practices, the resilience of rice production systems to biotic and abiotic stresses can be enhanced, contributing to future food security. The successful integration of these technologies is essential in regions where rice is a staple crop, particularly in Asia, where population growth and climate-related risks are intensifying (Seck *et al*., 2012). This holistic approach will be key in meeting the challenge of producing more food with fewer resources and minimizing the environmental footprint of rice cultivation.

Addressing climate change impacts

The effects of climate change must be taken into account in rice enhancement innovations, such as the creation of varieties resistant to harsh weather and pest pressure. Breeding for climate resilience is essential for future-proofing rice production (Bailey-Serres *et al*., 2019). Recent advancements in genomic tools have further accelerated efforts to breed climate-resilient rice varieties. Genomic selection and CRISPR-Cas gene-editing technology allow scientists to target specific genes associated with abiotic stress tolerance, such as heat, drought and salinity, enabling faster development of resilient varieties (Shen *et al*., 2022). Additionally, the integration of traditional breeding methods with modern biotechnological approaches has led to the creation of “climate-smart” rice varieties that not only survive harsh environmental conditions but also maintain high yield potential and nutritional quality (Swamy *et al*., 2021).

Adapting rice cultivation practices to climate change also requires innovation in water and nutrient management. Efficient water-saving techniques, such as alternate wetting and drying (AWD) and the System of Rice Intensification (SRI), help mitigate the impacts of drought and water scarcity while enhancing plant health (Koutroubas *et al*., 2021). Sustainable intensification practices, coupled with climate-resilient varieties, provide a comprehensive approach to safeguarding rice production in a changing climate.

Enhancing resource use efficiency

Improving resource use efficiency, especially in water and nutrient management, is crucial for sustainable rice production, given the increasing pressures of climate change and a growing global population. Advanced technologies play a significant role in optimizing resource utilization, leading to enhanced productivity while minimizing environmental impacts. Precision agriculture techniques, such as soil moisture sensors, satellite imageryand drone technology, enable farmers to monitor and manage water usage more effectively. These technologies help identify specific irrigation needs, thereby reducing water wastage and enhancing crop resilience during periods of drought (Zhang *et al*., 2022).

In addition to water management, optimizing nutrient application is essential for maintaining soil health and crop yield. Innovations in nutrient management, such as the use of controlled-release fertilizers and precision fertilization techniques, allow for the targeted application of nutrients based on soil tests and crop requirements. This approach not only increases nutrient uptake efficiency but also reduces the risk of environmental pollution from excess fertilizer runoff (Kumar *et al*., 2022). Furthermore, integrating technologies like decision support systems (DSS) can assist farmers in making informed choices about irrigation and fertilization, ultimately enhancing resource use efficiency (Li *et al*., 2021).

Agroecological approaches

Agroecological practices, which promote biodiversity and ecological balance, will gain traction in sustainable rice production. Practices such as crop rotation, intercropping and agroforestry can enhance soil health, increase pest resilience and improve overall farm productivity. By promoting diverse cropping systems, farmers can reduce reliance on chemical inputs and foster a more sustainable farming environment (Lal, 2020). The adoption of agroecological practices in sustainable rice production not only enhances ecological balance but also contributes to the resilience of farming systems against the increasing challenges posed by climate change. One key aspect of these practices is their ability to optimize nutrient cycling within the agroecosystem. By incorporating cover crops and green manures, farmers can improve soil fertility naturally, increase organic matterand enhance microbial activity in the soil, which is essential for nutrient availability. This not only reduces the need for synthetic fertilizers but also helps in building a more robust soil structure (Garnett *et al*., 2013).

The future of rice improvement in India faces several significant challenges. Here are some of the key issues:

Key challenges

Climate change

Impact: Increasing temperatures, erratic rainfalland extreme weather events affect rice yields and quality.

Solution: Developing climate-resilient rice varieties that can withstand these changes.

Water scarcity

Impact: Rice is a water-intensive cropand depleting groundwater levels pose a significant threat.
Solution: Implementing water-saving techniques like Alternate Wetting and Drying (AWD) and drip irrigation.

Soil health

Impact: Continuous rice cultivation can lead to soil degradation and nutrient depletion.
Solution: Adopting integrated nutrient management and cover cropping to maintain soil fertility.

Labor shortages

Impact: Migration and urbanization have led to a decline in agricultural labor availability.
Solution: Mechanization and the use of technology to reduce dependency on manual labor.

Pest and disease management

Impact: Pests and diseases can cause significant yield losses.
Solution: Using Integrated Pest Management (IPM) and developing pest-resistant rice varieties through gene editing technologies like CRISPR-Cas9.

Socioeconomic factors

Impact: Rising production costs, fuel prices and socioeconomic changes such as urbanization and less interest in agriculture among youth.
Solution: Policy support and incentives to make agriculture more attractive and sustainable.

Innovative practices and solutions

The Fig 7 outlines a range of innovative practices and solutions aimed at improving rice cultivation, addressing challenges such as productivity, sustainabilityand resilience. The strategies are categorized into key areas:

Climate-resilient varieties

The development of climate-resilient rice varieties is crucial for ensuring food security in the face of climate change. Researchers are focusing on breeding varieties that can withstand extreme environmental conditions such as drought, salinity and flooding. For instance, traditional breeding techniques combined with advanced genomics are being employed to identify and incorporate genes associated with stress tolerance into high-yielding rice cultivars.

Moreover, the application of CRISPR-Cas9 technology is revolutionizing the breeding process by allowing for precise genetic modifications. This innovative gene-editing tool enables scientists to enhance resistance to pests and diseases, which can significantly reduce crop losses and improve yield stability. For example, researchers are using CRISPR to edit specific genes responsible for susceptibility to bacterial blight and blast diseases, leading to the development of rice varieties that maintain high productivity even under pest pressure (Zhou *et al*., 2020).

Water management techniques

Efficient water management is critical for sustainable rice production, especially in regions facing water scarcity. Techniques such as alternate wetting and drying (AWD) not only conserve water but also improve rice yields by promoting deeper root growth and enhancing the plant's resilience to drought. Additionally, innovative irrigation systems, such as drip irrigation and sprinkler systems, are being implemented to optimize water use and ensure that rice crops receive adequate moisture without excessive water waste (Khan *et al*., 2021).

Agroecological practices

Incorporating agroecological practices, such as crop diversification and agroforestry, enhances the resilience

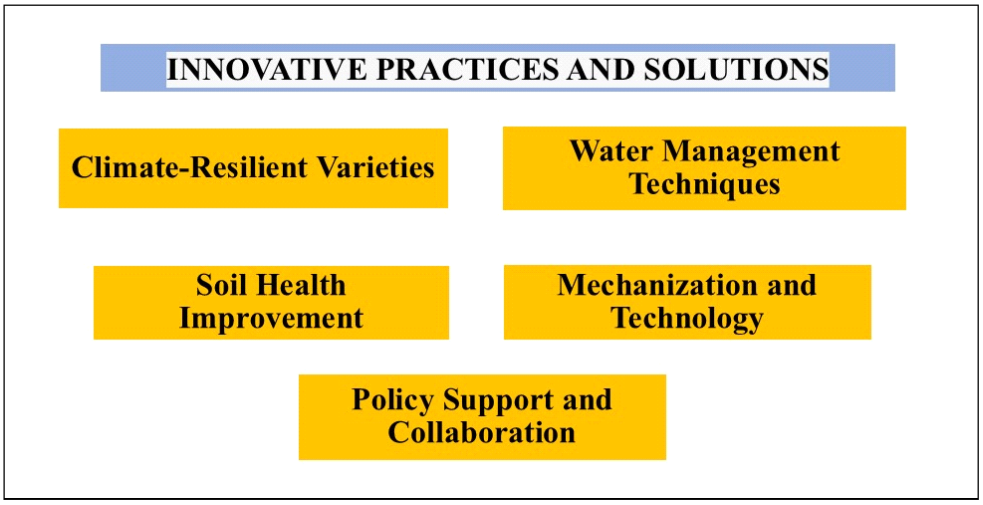


Fig 7: Innovative practices and solutions for rice improvement.

of rice farming systems. By growing rice alongside legumes or integrating tree species, farmers can improve soil health, increase biodiversity and create more sustainable ecosystems. These practices not only provide additional income sources but also promote natural pest control and reduce the need for chemical inputs (Altieri, 2018).

Use of dgital agriculture technologies

The adoption of digital agriculture technologies, including precision agriculture tools, mobile applications and data analytics, can significantly enhance decision-making in rice production. These technologies allow farmers to access real-time data on soil moisture, weather conditionsand crop health, enabling them to make informed decisions regarding irrigation, fertilization and pest management. For instance, mobile apps that provide weather forecasts and pest alerts can help farmers optimize their operations and reduce losses (Wolfert *et al*., 2017).

Participatory breeding and farmer involvement

Engaging farmers in the breeding process through participatory breeding programs can lead to the development of varieties that are better suited to local conditions and farmer preferences. By incorporating local knowledge and practices, researchers can create more relevant and adaptable rice varieties, fostering a sense of ownership among farmers. This collaboration not only enhances the adoption of new technologies but also strengthens the resilience of farming communities (Sperling *et al*., 2019).

CONCLUSION

Recent advancements in rice breeding and cultivation technologies have the potential to significantly improve rice yields, qualityand resilience. These innovations are essential for meeting the growing global demand for rice. Adopting sustainable practices is crucial to ensure the long-term viability of rice production systems. Sustainable practices help to mitigate environmental impacts and promote resource conservation.

To increase rice production and support global food security, research, innovation and capacity building must continue. To achieve these objectives, cooperation between scientists, decision-makers and farmers will be essential. To reduce the yield gap between areas prone to abiotic stresses and irrigated fields, it is essential to consider multiple abiotic stress tolerance traits alongside high yield potential and disease resistance. Developing submergence- tolerant cultivars has required stress-specific screening methods, as directly assessing tolerance is more complex than it appears. Our knowledge of how rice genes respond to stress is expanding rapidly. However, our understanding of how these genetic changes translate into plant growth and crop performance under stress remains limited. A concerted effort is needed to synthesize this information and transform the promising results of genomics into practical tools and guidelines for plant breeders.

In recent years, advancements in rice breeding have focused on developing high-yielding, stress-tolerant and climate-resilient varieties. These include the integration of biotechnological tools such as marker-assisted selection (MAS), genomic selection (GS) and CRISPR-Cas9 for precise gene editing. These tools are instrumental in addressing challenges such as drought, salinity and pest resistance, allowing farmers to optimize production even in adverse environmental conditions.

Conflict of interest

The authors declare that there are no conflict of interest.

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