Plant Archives Vol. 26, Supplement 2, 2026 pp. 1107-1118 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.supplement-2.129

EMERGING TRENDS IN GLOBAL RICE SYSTEMS: INTEGRATING GENOMIC INNOVATIONS FOR SUSTAINABLE PRODUCTION

Ch Sai Nayan Raju[1*], Priti A. Sonkamble[1], Suneetha Kota[2], Ghorade R. B.[1], M. P. Meshram[3], Shinde Jagannath Vishwanath[1] and Vinod Kogade[1]

[1]Genetics and Plant Breeding, Department of Agricultural Botany, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra , 444104, India

[2]Plant Breeding, Crop Improvement Section, ICAR-Indian Institute of Rice Research, Rajendranagar, Hyderabad, 500 030, Telangana State, India,

[3]Agriculture Research Station, Sakoli , Dr.Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra , 44410. India

*Corresponding author E-mail: docternayan@gmail.com

ORCID ID-0000-0002-8171-6814

(Date of Receiving : 24-02-2026; Date of Revision : 06-04-2026; Date of Acceptance : 01-05-2026)

ABSTRACT

Rice (*Oryza sativa* L.) is one of the most important staple crops globally, serving as the primary source of nourishment for nearly half of the world's population and playing a crucial role in food security, particularly in Asia, which accounts for approximately 90% of global production. Despite advancements in breeding, irrigation, and agricultural technologies, a significant gap persists between potential and actual yields, especially in developing regions where productivity is constrained by poor soil fertility, limited input availability, and socio-economic limitations. Climate change further intensifies these challenges through increased variability in rainfall, frequency of droughts and floods, and rising temperature stress, all of which threaten yield stability and resource availability. This review synthesizes existing research on agronomic practices, environmental constraints, technological advancements, and socio-economic factors affecting rice productivity. It highlights the role of genome editing technologies, particularly CRISPR-based approaches, in enabling precise and targeted development of climate-resilient and high-yielding rice varieties. Emphasis is given to thermotolerance and abiotic stress responses, which significantly affect plant growth, grain quality, and overall productivity. The importance of trait stacking for combining multiple stress resistance traits with desirable grain quality attributes is also discussed. The review further examines the integration of artificial intelligence and machine learning in breeding programs to enhance selection accuracy and accelerate varietal development. In addition, sustainable agronomic practices such as Alternate Wetting and Drying (AWD) and Direct Seeded Rice (DSR) are considered for improving water-use efficiency, reducing labor requirements, and minimizing environmental impacts. Integrated farming systems, including rice–fish and rice–duck models, are also discussed for their role in enhancing resource-use efficiency, nutrient recycling, and farm sustainability.

***Keywords*:** Yield gap; climate change; genome editing; CRISPR/Cas9; thermotolerance; artificial intelligence; sustainable rice production.

Introduction

Rice (*Oryza sativa* L.) remains one of the most important staple crops globally (Muthayya *et al*., 2014) earning it the designation of a "global grain." It provides the primary source of nourishment for nearly half of the world's population and plays a crucial role in global nutrition and food security, especially across Asia. Globally, rice is cultivated on approximately 165 million hectares, with an annual production of about 508.9 million tonnes. (Indiastat 2022-2023). Approximately 90% of global rice production and consumption is concentrated in Asia (Singh *et al*., 2015). India ranks second after China, with a production of about 129.47 million metric tonnes (Indiastat, 2022–23). Beyond its role in food supply, rice cultivation contributes significantly to rural livelihoods by generating income, strengthening agricultural systems, and supporting national economies (Neglo *et al*., 2021). As population growth continues and reliance on rice-based diets persists in several regions (Bandumula, 2018). Therefore, understanding the factors influencing rice productivity is essential for ensuring long-term food security and socio-economic stability (Verma *et al*., 2021). Over recent decades, global demand for rice has steadily increased, driven by population expansion, urbanization, and rising living standards, particularly in developing countries (Samal *et al*., 2022; Sokra *et al*., 2024). Despite advancements in breeding, irrigation, and agricultural technologies, a significant gap persists between potential and actual yields (Anderson *et al*., 2016). This yield gap is especially pronounced in developing regions, where smallholder farmers face multiple challenges, including agronomic limitations, environmental stress, and socio-economic constraints (John & Fielding, 2024; Somaly & Sokra, 2024). In many areas, productivity remains below attainable levels due to poor soil fertility, limited access to fertilizers, and constraints in input availability (Fahad *et al*., 2019; Papademetriou *et al*., 2000; Prasad *et al*., 2017). With the global population expected to be 10 billion, enhancing productivity and improving resource-use efficiency have become increasingly important. (Mohd-Hanafiah *et al*., 2020). Climate change further exacerbates these challenges, introducing variability in rainfall patterns, increasing the frequency of droughts and floods, and intensifying heat stress and salinity intrusion in coastal regions (Kumar *et al*., 2022; Gopalakrishnan *et al*., 2019). These factors threaten yield stability and increase the vulnerability of farming communities (Altieri *et al*., 2015; Somaly *et al*., 2025). At the same time, the availability of arable land and freshwater resources is declining, while competition for water among agricultural, industrial, and domestic sectors continues to intensify (Tahir *et al*., 2024). Additional pressures such as soil degradation, pest outbreaks, and shifting disease dynamics further complicate rice production systems (Altieri *et al*., 2024). These constraints highlight the urgent need for climate-resilient production systems, adaptive management strategies, and technological innovations (Shukla *et al*., 2025). Given these multifaceted challenges, there is a growing need for an integrated synthesis of existing research (Chang *et al*., 2025). Although numerous studies have examined agronomic practices, technological advancements, socio-economic factors, and environmental constraints, the available evidence remains fragmented (Lemarié & Marette, 2022; Rizzo *et al*., 2024). A systematic review approach enables the consolidation of this information, facilitating the identification of key trends and research gaps (Medeiros *et al*., 2021). Such insights are essential for informing policy decisions and guiding future research toward sustainable and resilient rice production systems (Gava *et al*., 2020). Advance genomic technologies have transformed rice improvement, strategies and enabling precise targeted development of climate resilient and high yield rice varieties. These challenges collectively highlight the need for integrating advanced genomic tools with sustainable management practices to ensure resilient and efficient rice production systems. These challenges collectively underscore the need to integrate advanced genomic tools with sustainable management practices to achieve resilient and efficient rice production systems. Although extensive research exists across disciplines, the available evidence remains fragmented, highlighting the need for comprehensive review.

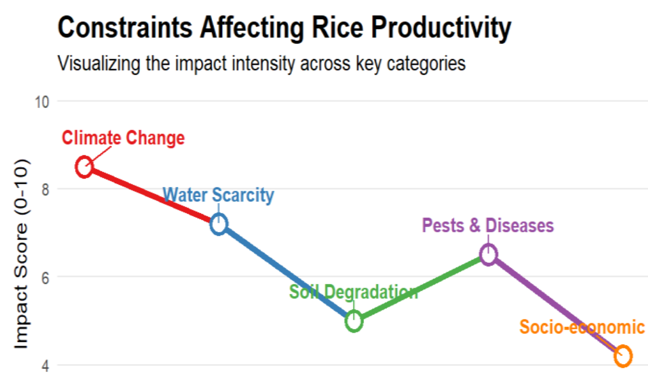

Fig. 1 : Relative Impact of Environmental and Systemic Constraints on Rice Productivity

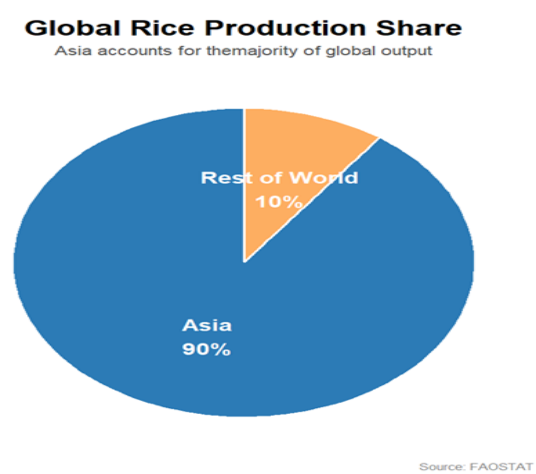

Fig. 2 : Relative share of total global rice output: Asia vs. Rest of World.

Genome Editing and CRISPR technology

The emergence of genome editing technologies has addressed several limitations associated with conventional breeding approaches, marking a new phase in crop improvement. Genome editing employs engineered site-specific nucleases (SSNs) to introduce precise modifications at targeted genomic loci (Mishra *et al*., 2018). Among these, the CRISPR-Cas9 system is recognized as one of the most advanced and widely utilized tools in plant biology (Belhaj *et al*., 2015; Weeks *et al*., 2016).Rice serves as an important model system for functional genomics due to its relatively small genome, extensive genetic resources, high transformation efficiency, and genomic synteny with other cereal crops. Consequently, it has been extensively used to evaluate genome editing technologies and to elucidate gene functions for crop improvement (Li *et al*., 2012; Feng *et al*., 2013; Xu *et al*., 2014, 2016; Wang *et al*., 2016). Traditional breeding methods are often labor-intensive and time-consuming, limiting the speed of varietal development. In contrast, modern genome editing technologies enable precise and targeted genetic modifications, facilitating the rapid development of improved crop varieties with enhanced traits such as disease resistance, abiotic stress tolerance, and increased productivity (Nerkar *et al*., 2018; Altpeter *et al*., 2016). The CRISPR-Cas system, in particular, functions as a precision breeding tool by enabling site-specific genome modifications without the integration of foreign DNA (non-transgenic), thereby offering a highly efficient and versatile approach for crop improvement (Jinek *et al*., 2012; Zhang *et al*., 2016; Bandyopadhyay *et al*., 2020; Ma *et al*., 2020). Thus, genome editing technologies, particularly CRISPR-based approaches, provide a strong foundation for developing climate-resilient rice varieties, which can be further enhanced by targeting specific stress-responsive traits. In this context, the application of genome editing technologies has been increasingly directed toward improving tolerance to major abiotic stresses, particularly high temperature, drought, and salinity, which critically affect rice productivity under changing climatic conditions.

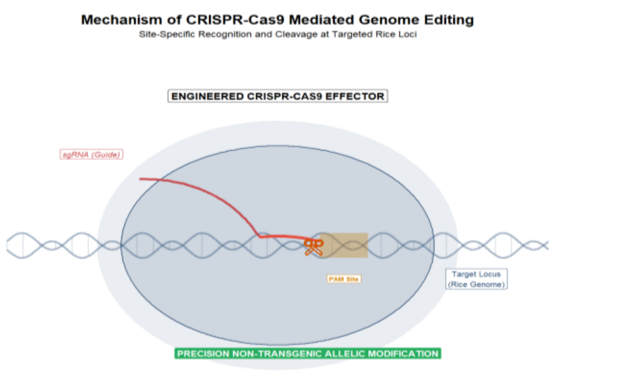

Fig. 3: Structural Model of CRISPR-Cas9 Mediated Genome Editing in Rice. Schematic representation illustrating the biochemical recognition of a targeted genomic locus. The engineered Cas9 effector complex is guided by a single-guide RNA (sgRNA) to a specific DNA sequence adjacent to a Protospacer Adjacent Motif (PAM). The diagram highlights the "Seed Region" of the sgRNA, where base-pairing stability is critical for inducing a precise double-strand break (DSB), indicated by the cleavage symbol. This mechanism facilitates targeted, non-transgenic allelic modifications, offering a rapid and versatile foundation for enhancing rice resilience against climate-induced abiotic and biotic stressors.

Thermotolerance and Stress Traits

Among abiotic factors, high temperature is considered one of the most critical stresses with a significant impact on crop yield (IPCC, 2014). In tropical and subtropical regions, rice productivity is particularly affected by elevated temperatures (Shah *et al*., 2011), which can lead to grain sterility and substantial yield reduction (Prasad *et al*., 2006; Beena *et al*., 2018). Thermotolerance can be induced through gradual exposure to increasing temperatures, allowing plants to acclimate to lethal conditions similar to natural environments (Larkindale *et al*., 2005). This acclimation involves mechanisms that help avoid heat damage and repair heat-sensitive cellular components (Kheir *et al*., 2012). High temperature stress adversely affects plant growth and development, resulting in reduced seed quality, poor germination, low seedling vigor, decreased tiller and panicle number, impaired pollination and fertilization, reduced spikelet fertility, and lower pollen viability (Shrestha *et al*., 2022). It also disrupts key physiological processes, including membrane stability, photosynthesis, carbohydrate metabolism, and phytohormone balance (Xu *et al*., 2021). During the grain-filling stage, heat stress reduces grain weight and increases chalkiness, thereby affecting grain quality (Chandran *et al*., 2022). Germination, being a critical stage of the plant life cycle, is highly sensitive to temperature, highlighting the importance of understanding gene expression changes under high-temperature conditions. Rising global temperatures pose a serious challenge to agriculture, with projections indicating an increase of 2–6 °C by the end of the century (Peck and Teisberg, 1992). High temperature stress causes severe damage to rice crops, particularly during key growth stages such as germination, seedling establishment, and the reproductive phase (Jagadish *et al*., 2010; Sailaja *et al*., 2014a; Shi *et al*., 2015). Genome editing tools such as CRISPR/Cas9 enable rapid and precise improvement of stress tolerance compared to conventional breeding methods (Ahmad, 2023). CRISPR is recognized as an efficient and versatile system for editing plant genomes (Song *et al*., 2016; Zhang *et al*., 2021) and has been successfully applied to enhance yield, quality, nutritional value, and tolerance to both biotic and abiotic stresses in rice (Romero and Gatica-Arias, 2019; Tabassum *et al*., 2021). In addition to heat stress, efforts are also directed toward improving tolerance to drought and salinity, which are increasingly prevalent under changing climatic conditions. Therefore, improving thermotolerance and stress resilience through advanced breeding and genome editing approaches is essential for sustaining rice productivity under changing climatic conditions Given the multifaceted impact of abiotic stresses on both yield and grain quality, breeding strategies are increasingly focused on combining multiple stress tolerance traits with desirable quality attributes through trait stacking approaches.

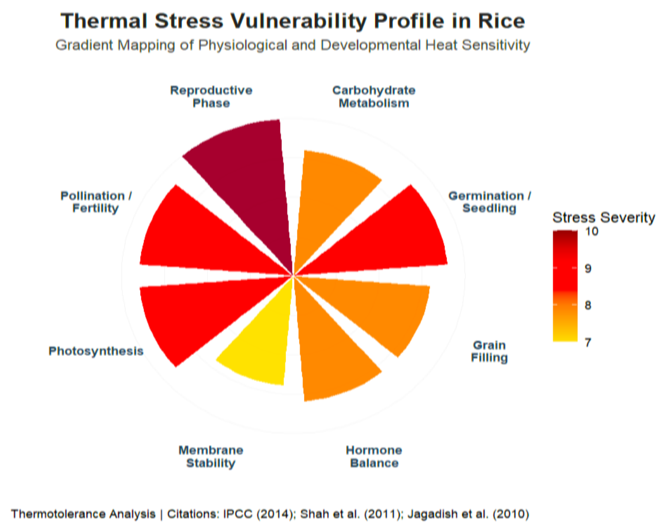

Fig. 4 : Thermal stress vulnerability map across the rice ontogeny. The radial gradient illustrates the differential sensitivity of specific growth stages and physiological processes to rising global temperatures. The heatmap scale (Yellow to Red) denotes the severity of impact, identifying the reproductive phase and photosynthesis as the most thermally sensitive parameters, contributing significantly to grain sterility and yield instability in tropical rice production environments.

Trait Stacking and Grain Quality

The emergence of new diseases, pest biotypes, and changing climatic conditions has intensified the need for sustainable crop development with enhanced resistance to both biotic and abiotic stresses (Hasan *et al*., 2015). This has led to the adoption of gene stacking strategies, where multiple resistance genes are combined into high-yielding cultivars to achieve broad-spectrum and durable protection. Such gene pyramiding enables crops to withstand multiple stresses simultaneously while maintaining productivity under unfavorable environmental conditions. Advances in molecular biology and DNA-based markers have facilitated the efficient transfer and tracking of resistance genes against major biotic stresses such as bacterial blight, blast, and gall midge, as well as abiotic stresses including submergence and salinity. Marker-assisted approaches enable precise identification of plants carrying multiple desirable genes, thereby accelerating the development of improved cultivars (Das *et al*., 2015). Abiotic stresses such as heat, drought, submergence, and nutrient deficiencies create suboptimal conditions that adversely affect germination, seedling establishment, vegetative growth, flowering, grain filling, and overall productivity (Jeyasri *et al*., 2021; Banerjee and Roychoudhury, 2020; Beena *et al*., 2021a). These stresses significantly impair crop growth, grain quality, and yield in rice (Pravallika *et al*., 2020; Pathak *et al*., 2021). Moreover, certain abiotic conditions can favor the occurrence of biotic stresses, further aggravating yield and quality losses (Narsai and Whelan, 2013). Rice grain quality is determined by attributes such as grain appearance, mineral composition, amylose and amylopectin content, aroma, and cooking properties (Chakraborti *et al*., 2021). Abiotic stresses, particularly during the grain-filling stage, negatively affect milling quality, increase grain chalkiness, and alter starch composition (Lanning and Siebenmorgen, 2013). Among these, high temperature has the most pronounced effect on grain quality, reducing both physical and sensory characteristics of milled rice (Liu *et al*., 2021). Although several studies have explored rice grain biochemistry, limited research has focused on the combined effects of multiple abiotic stresses on grain quality (Liu *et al*., 2013; Kadam *et al*., 2014). Hence, integrating multiple stress resistance traits with grain quality improvement remains a critical strategy for developing high-performing and resilient rice cultivars .To effectively integrate multiple stress resistance traits with grain quality attributes, advanced computational approaches such as artificial intelligence and machine learning are increasingly being utilized to enhance selection accuracy and accelerate breeding programs.

AI-Assisted Breeding

Plant breeding has evolved progressively from Breeding 1.0 to Breeding 4.0. According to Wallace *et al*. (2018), Breeding 1.0 was characterized by farmer-led selection, Breeding 2.0 by the application of statistical methods and experimental design, and Breeding 3.0 by the integration of genetic and genomic information. Breeding 4.0, driven by advances in genetics and information technologies, is now shaped by artificial intelligence (AI), multi-omics data, and genome editing tools (Wallace *et al*., 2018). Artificial intelligence, defined as the simulation of human intelligence processes such as learning, reasoning, prediction, and self-correction, is emerging as a key component of modern breeding programs (Farooq *et al*., 2024). It supports environmentally sustainable crop improvement by enhancing productivity and contributing to global food security. The adoption of high-throughput multi-omics approaches has enabled the generation of large-scale datasets encompassing phenotypic, biochemical, physiological, and genomic information. These datasets provide valuable insights for targeted crop improvement. The complexity and scale of such data necessitate the use of advanced computational tools, bioinformatics methods, and machine learning (ML) techniques for efficient analysis and interpretation. These approaches facilitate precise phenotyping and genomic prediction, enabling the accurate selection of superior genotypes. The integration of AI with genomic and phenomic data thus offers powerful opportunities to accelerate varietal development and enhance breeding efficiency, particularly under the challenges posed by climate change. Consequently, AI-driven breeding approaches are expected to play a critical role in advancing precision breeding and the development of next-generation rice varieties (Sadhan *et al*., 2025). While advancements in AI-driven breeding enhance genetic improvement, achieving sustainable increases in rice productivity also requires the adoption of resource-efficient agronomic practices under field conditions.

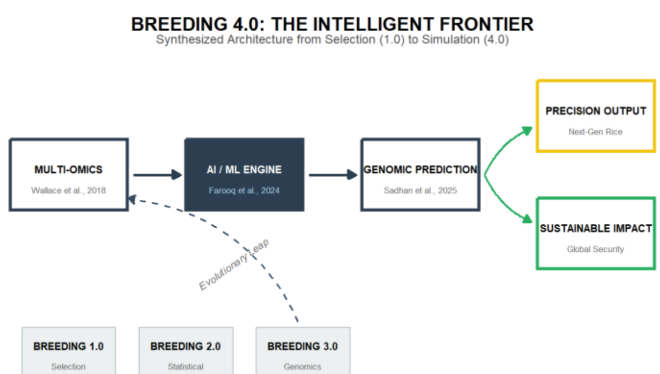

Fig. 5 : The Intelligent Frontier of Breeding 4.0 The evolutionary trajectory of plant breeding, showing the transition from traditional farmer-led selection (Breeding 1.0) to an AI-integrated precision pipeline (Breeding 4.0). The framework emphasizes the role of the AI/ML engine in synthesizing multi-omics inputs into genomic predictions, ultimately resulting in next-generation rice varieties with enhanced climate resilience and global food security impact (adapted from Wallace *et al*., 2018).

Sustainable Intensification in Rice Systems

Alternate Wetting and Drying (AWD)

Although rice plays a crucial role in global food security, its conventional cultivation under continuously flooded conditions requires substantially higher water inputs compared to other cereal crops (Pimentel *et al*., 2004). With water scarcity currently affecting nearly 4 billion people worldwide (Mekonnen and Hoekstra, 2016), there is an urgent need to adopt agronomic practices that can reduce water consumption while sustaining or enhancing crop productivity. One such approach is Alternate Wetting and Drying (AWD), an irrigation management practice designed to optimize water use in rice systems (Linquist *et al*., 2014; Lampayan *et al*., 2015). A low wage rate and as asured supply of adequate water are conditions favorable for transplanting. Incentives for direct seeding increase when water availability is low (or uncertain) and wage rates are high (Pandey & Velasco 2005). In AWD, fields are not kept continuously flooded; instead, irrigation is applied intermittently, allowing the soil to dry to a certain threshold before re-irrigation. This cyclic transition between saturated and unsaturated soil conditions enables more efficient water management. Studies have shown that AWD can reduce water input by approximately 23% compared to traditional continuously flooded systems (Bouman and Tuong, 2001). In addition to water savings, AWD contributes to the mitigation of greenhouse gas emissions, particularly methane (CH_4) (Wassmann *et al*., 2010; Li *et al*., 2006). AWD can lower the global warming potential (combined CH_4 and N_2O emissions) by 45–90% relative to continuously flooded rice cultivation (Linquist *et al*. 2014). Given that global anthropogenic greenhouse gas emissions are estimated at approximately 48 Gt CO_2 equivalent per year (Montzka *et al*., 2011), the adoption of AWD represents a significant strategy for improving the environmental sustainability of rice production systems. Building such water-efficient practices, other innovations such as Direct Seeded Rice (DSR) further contribute to reducing labor, water use, and environmental impacts in modern rice cultivation systems. contribute to reducing labor, water use, and environmental impacts in modern rice cultivation systems.

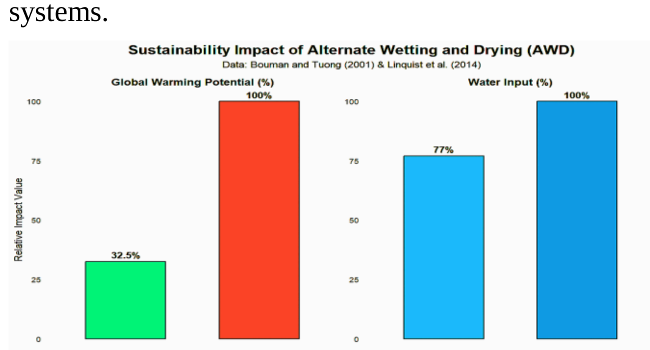

Fig. 6 : Relative impact of Alternate Wetting and Drying (AWD) compared to conventional flooded systems on global warming potential (%) and water input (%) in rice cultivation

Table 1 : Comparative assessment of Transplanted Rice (TPR) and Alternate Wetting and Drying (AWD) systems

Parameter	TPR (Transplanted Rice)	AWD (Alternate Wetting & Drying)	Source
Water Use	High due to continuous flooding, puddling, evaporation, and percolation losses	Reduced water use compared to TPR through intermittent irrigation	Bouman & Tuong (2001)
Methane Emissions (CH_4)	High under continuously flooded conditions	Reduced methane emissions due to periodic soil aeration	Linquist *et al*. (2014)
Yield Performance	Generally stable	Comparable to TPR	Lampayan *et al*. (2015)
Labour Requirement	High (nursery preparation, puddling, transplanting)	Moderate labour requirement	Pandey & Velasco (2005)
Cost of Cultivation	High due to water and labour inputs	Reduced input cost	Flinn & Mandac (1986)
Water Management	Continuous flooding	Alternate wetting and drying cycles	Linquist *et al*. (2014)
Environmental Impact	Higher greenhouse gas emissions	Lower environmental impact	Linquist *et al*. (2014)
Suitability	Suitable where water and labour are abundant	Suitable for water-saving and sustainable production systems	Pandey & Velasco (2005)

Direct Seeded Rice (DSR)

Direct-seeded rice is recognized as a resource-conserving technology with several advantages over the traditional transplanted puddled rice (TPR) system. It eliminates the need for nursery raising, puddling, and transplanting, thereby significantly reducing water use. This method can lower labour requirements by nearly 40% and save up to 60% of water by minimizing losses associated with nursery preparation, field operations, seepage, percolation, and evaporation (Singh *et al*., 2018). Direct seeding has been a widely practiced method of rice establishment in developing countries since the 1950s (Pandey and Velasco, 2005). In contrast, the traditional transplanting system (TPR) involves puddling, which forms a hard pan below the plough layer and reduces soil permeability. This practice results in significant water losses through puddling, surface evaporation, and percolation. With the progressive depletion of both surface and groundwater resources, water availability has become a major constraint in rice production (Farooq *et al*., 2009a). In addition to water limitations, TPR is highly labor-intensive, requiring substantial effort for nursery raising, seedling uprooting, puddling, and transplanting operations. The associated high labor demand and rising labor costs have significantly reduced profit margins (Pandey and Velasco, 1999). In recent years, many Southeast Asian countries have shifted from TPR to DSR systems (Pandey and Velasco, 2002). This transition has been largely driven by labor shortages and increasing wages, which often delay transplanting operations (Chan and Nor, 1993). While transplanting is favored under conditions of low labor cost and sufficient water availability, DSR is more suitable in environments characterized by water scarcity and high labor costs (Pandey and Velasco, 2005). The adoption of DSR in lowland rice systems has the potential to substantially reduce production costs (Flinn and Mandac, 1986). However, the lack of varieties specifically developed for DSR remains a major limitation. Most existing varieties, originally bred for transplanting systems, are not well adapted to direct seeding conditions, particularly during early seedling establishment under oxygen-deficient environments. Consequently, farmers often compensate by increasing seeding rates by two to three times, which raises input costs. Therefore, the development of DSR-suitable varieties with improved germination and early growth under non-flooded conditions is essential. These challenges highlight the need for integrated weed and nutrient management strategies, which remain critical research priorities for optimizing DSR-based production system.

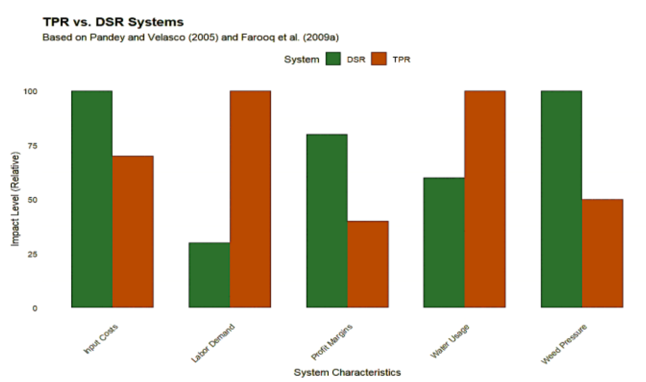

Fig. 7 : Relative comparison of transplanted rice (TPR) and direct-seeded rice (DSR) systems in terms of input costs, labor demand, profit margins, water usage, and weed pressure.

Table 2 : Comparison of Transplanted Rice (TPR) and Direct-Seeded Rice (DSR) Systems

Parameter	Transplanted Rice (TPR)	Direct-Seeded Rice (DSR)	Source
Establishment Method	Nursery raising followed by transplanting	Direct seeding into field	Pandey & Velasco (2005)
Water Requirement	High (puddling, flooding losses)	Lower water requirement	Farooq *et al*. (2009a)
Soil Condition	Puddled soil with hard pan formation	Non-puddled soil	Farooq *et al*. (2009a)
Labour Requirement	Very high (nursery, uprooting, transplanting)	Low labour requirement	Pandey & Velasco (1999)
Cost of Cultivation	High due to labour and water	Reduced cost	Flinn & Mandac (1986)
Time Requirement	Time-consuming	Faster establishment	Pandey & Velasco (2002)
Adaptability	Suitable with sufficient water and labour	Suitable under water scarcity & labour shortage	Pandey & Velasco (2005)
Yield Stability	Generally stable	Variable depending on management	Farooq *et al*. (2009a)
Weed Pressure	Lower due to standing water	Higher weed infestation	Farooq *et al*. (2009a)
Varietal Suitability	Well-developed varieties available	Limited varieties for DSR	Pandey & Velasco (2005)
Seed Rate	Normal	Higher (2–3×)	Pandey & Velasco (2005)
Constraints	High labour, water use	Poor emergence, lack of varieties	Farooq *et al*. (2009a)

Regenerative and Integrated Farming Systems

Rice–fish integrated farming systems

Rice–fish co-culture represents one of the oldest forms of integrated farming, widely recognized for enhancing resource-use efficiency and sustainability in rice-based systems (Liu *et al*., 2018). India, the second-largest global fish producer contributing nearly 8% of total output, produced approximately 19.8 million tonnes in 2024–2025, supporting around 30 million livelihoods (Economic Survey, 2025–2026). In rice–fish systems, compatible fish species such as common carp (*Cyprinus carpio*) and tilapia (*Oreochromis* spp.) are cultivated within paddy fields, enabling simultaneous production.

Despite the rapid growth of aquaculture, challenges such as high feed costs, environmental degradation, disease outbreaks, and greenhouse gas emissions have raised concerns regarding sustainability (Yuan *et al*., 2019; Robb *et al*., 2017). In this context, integrating fish culture within rice fields offers a viable alternative by optimizing land and water use while reducing external inputs. Such systems improve nutrient recycling, enhance farm productivity, and provide an additional income source for smallholder farmers. Beyond economic benefits, rice–fish systems contribute to ecological sustainability by reducing chemical inputs, improving biodiversity, and enhancing system resilience. Building on this concept of ecological integration, further diversification through the inclusion of livestock components has led to the development of more complex and efficient farming systems such as rice–duck integration (Priyanka *et al*., 2022). Consequently, integrating fish and rice cultivation on the same land to optimize water use provides a sustainable production strategy, and this integrated synergy can be further enhanced by incorporating livestock components such as ducks to develop more holistic farming systems.

Rice-duck integrated farming systems

Integrated duck-based farming systems are increasingly adopted worldwide due to their ecological and economic advantages. Common models include duck–rice, duck–fish, and duck–rice–fish systems. In rice–duck systems, ducks are introduced into paddy fields where they naturally control weeds and insect pests, reducing the need for chemical inputs. Their movement in the field enhances soil aeration and promotes better nutrient distribution, ultimately improving crop growth and yield. More complex systems such as duck–rice–fish and duck–rice–fish–azolla integrate multiple biological components to establish efficient nutrient cycling. In these systems, duck droppings serve as organic fertilizer, stimulating plankton growth that supports fish production, while nutrient-rich water benefits rice cultivation (Sapkota *et al*., 2022). Such integrated approaches enhance productivity, reduce environmental impacts, and improve farm profitability. Thus, the integration of duck-based systems in rice cultivation enhances nutrient recycling, improves ecological balance, and supports more efficient and sustainable rice-based farming systems. An overview of integrated rice-based farming systems, including their components, benefits, and associated challenges, is presented in Table given below

Table 3 : Integrated rice-based farming systems and their components, benefits, and challenges

System	Components	Key Benefits	Limitations/Challenges	Source
Rice–Fish System	Rice + fish species (e.g., *Cyprinus carpio*, *Oreochromis* spp.)	Optimizes land and water use; provides additional income; improves nutrient recycling; enhances sustainability	High feed cost; shortage of nursery ponds; disease outbreaks; environmental issues such as eutrophication and biodiversity loss	Liu *et al.* (2018); Yuan *et al.* (2019); Robb *et al.* (2017)
Duck–Rice System	Rice + ducks	Natural weed and pest control; improved soil aeration; enhanced crop growth and yield	Requires management of ducks within fields	Sapkota *et al.* (2022)
Duck–Fish System	Ducks + fish	Duck waste acts as feed for fish; mutual nutrient exchange	System management complexity	Sapkota *et al.* (2022)
Duck–Rice–Fish System	Rice + ducks + fish	Improved nutrient cycling; reduced pollution; ecological balance; enhanced productivity	Requires integrated management practices	Sapkota *et al.* (2022)

Proposed Conceptual Framework for Sustainable Rice Production

The increasing complexity of unprecedented and persisting challenges associated with rice production, including climate change, resource limitations, and yield unpredictability, necessitates an integrated and holistic approach. Although substantial progress has been made in individual domains such as genomic improvement, agronomic management, and farming system diversification, these efforts often remain fragmented. Therefore, a unified conceptual framework is essential to synthesize these advancements and guide the development of sustainable rice production systems. The proposed framework integrates three interconnected levels: genetic improvement, crop management, and farming system integration. At the genetic level, advanced breeding approaches, including genome editing like CRISPR/cas9 and trait stacking, focus on developing climate-resilient and high-yielding rice varieties with enhanced tolerance to abiotic and biotic stresses. These innovations provide the foundational and fundamental capacity for improving productivity under changing environmental conditions. At the crop management level, resource-efficient agronomic practices such as alternate wetting and drying (AWD) and direct-seeded rice (DSR) contribute to optimizing water use, reducing labor requirements, and minimizing environmental impacts. These practices augment the performance of improved genotypes under field conditions and support sustainable intensification of rice production. At the system level, integrated farming approaches such as rice–fish and rice–duck systems promote ecological balance through improved nutrient cycling, reduced chemical inputs, and diversification of farm outputs. These systems enhance resilience, increase farm profitability, and contribute to long-term sustainability. The interaction among these three levels creates a synergistic effect, where genetic advancements enhance crop adaptability to multi-environments, improved management practices optimize resource use, and integrated systems strengthen ecological sustainability. Together, these components form a comprehensive strategy for achieving resilient, productive, and environmentally sustainable rice production systems.

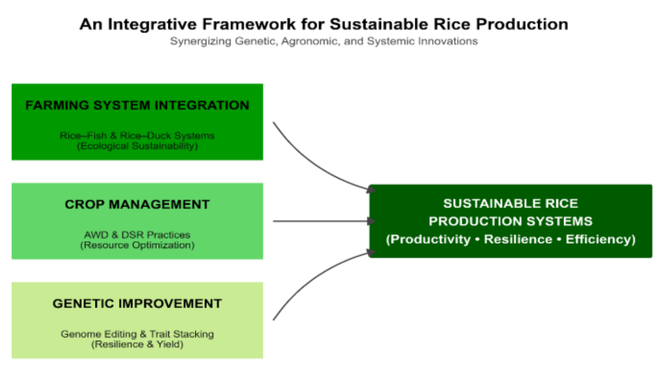

Fig. 8 : An Integrative Framework for Sustainable Rice Production: Synergizing Genetic, Agronomic, and Systemic Innovations

Conclusion

Rice continues to play a fundamental and important role in global food security, yet its productivity is increasingly challenged by a combination of climatic, environmental, and socio-economic constraints. The persistence of yield gaps, coupled with declining resource availability and increasing abiotic stresses such as heat, drought, and salinity, highlights the limitations of conventional production systems. These challenges are further intensified by climate change, which affects crop growth, yield stability, and grain quality. Advancements in genome editing technologies, particularly CRISPR/Cas-based approaches, have provided new opportunities for precise and efficient crop improvement. The ability to target specific genes associated with stress tolerance and productivity offers a strong foundation for developing climate-resilient rice varieties. In parallel, trait stacking strategies enable the combination of multiple stress resistance traits with desirable grain quality attributes, addressing both productivity and quality concerns. The integration of artificial intelligence and machine learning with genomic and phenomics data has further upgraded the efficiency of breeding programs by improving selection accuracy and accelerating varietal development. At the same time, sustainable agronomic practices such as Alternate Wetting and Drying (AWD) and Direct Seeded Rice (DSR) contribute to improved resource-use efficiency by reducing water consumption, labor requirements, and environmental impacts. Additionally, integrated farming systems, including rice–fish and rice–duck models, enhance nutrient recycling, ecological balance, and farm sustainability. If you encompass all of them, the available evidence emphasizes that no single approach is sufficient to address the complex hurdles facing rice production. Instead, the integration of advanced genomic tools, data-driven breeding approaches, and sustainable management practices is essential for developing resilient and efficient rice production systems capable of meeting future food demands. is essential for sustaining productivity, ensuring food security, and supporting resilient agricultural systems under changing climatic conditions.

Future insights

In Future the research on rice improvement should focus on strengthening understanding and implementing the integration of genomic technologies, advanced breeding approaches, and sustainable production systems. Genome editing tools such as CRISPR/Cas systems offer significant potential for precise manipulation of genes associated with stress tolerance, yield, and grain quality; however, further work is required to identify and validate key genes governing complex traits, particularly under field conditions and multi-environment (G×E interactions). Greater emphasis is needed on developing rice varieties with enhanced tolerance to multiple abiotic stresses, including high temperature, drought, and salinity, as these stresses increasingly occur in combination under changing climatic conditions. In this context, trait stacking approaches will play a critical role in combining multiple stress resistance traits with desirable quality characteristics to ensure both productivity and grain quality. The integration of artificial intelligence and machine learning with genomic and phenomics datasets is expected to further improve the efficiency and accuracy of breeding programs. Future efforts should focus on improving data integration, enhancing predictive models, and enabling their practical application in varietal development. In addition to genetic improvement, research should prioritize the refinement and large-scale adoption of resource-efficient agronomic practices such as Alternate Wetting and Drying (AWD) and Direct Seeded Rice (DSR), particularly under conditions of water scarcity and labor constraints. Furthermore, integrated farming systems, including rice–fish and rice–duck models, require continued evaluation to optimize system productivity, nutrient cycling, and environmental sustainability under diverse agro-ecological conditions. Overall, future research should aim to develop integrated and multidisciplinary approaches that combine genetic, technological, and management strategies to ensure sustainable and resilient rice production systems under evolving environmental and socio-economic conditions.

References

Anderson, W., Johansen, C., & Siddique, K. H. M. (2016). Addressing the yield gap in rainfed crops: A review. *Agronomy for Sustainable Development*, **36**(1), 18. https://doi.org/10.1007/s13593-015-0341-y

Altpeter, F., Springer, N. M., & Bartley, L. E. (2016). Advancing crop transformation in the era of genome editing. *Plant Cell*, **28**, 1510–1520. https://doi.org/10.1105/tpc.16.00196

Ahmad, M. (2023). Plant breeding advancements with "CRISPR-Cas" genome editing technologies will assist future food security. *Frontiers in Plant Science*, **14**, 1133036.

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, **35**(3), 869–890. https://doi.org/10.1007/s13593-015-0285-2

Altieri, M. A., Nicholls, C. I., Dinelli, G., & Negri, L. (2024). Towards an agroecological approach to crop health: Reducing pest incidence through synergies between plant diversity and soil microbial ecology. *Sustainable Agriculture*, **2**(1), 6. https://doi.org/10.1038/s44264-024-00016-2

Belhaj, K., Chaparro-Garcia, A., Kamoun, S., Patron, N. J., & Nekrasov, V. (2015). Editing plant genomes with CRISPR/Cas9. *Current Opinion in Biotechnology*, **32**, 76–84. https://doi.org/10.1016/j.copbio.2014.11.007

Beena, R., Kirubakaran, S., Nithya, N., Manickavelu, A., Sah, R. P., Abida, P. S., *et al*. (2021). Association mapping of drought tolerance and agronomic traits in rice (*Oryza sativa* L.) landraces. *BMC Plant Biology*, **21**(1), 484.

Beena, R., Vighneswaran, V., Sindumole, P., Narayankutty, M. C., & Voleti, S. R. (2018). Impact of high temperature stress during reproductive and grain filling stage in rice. *Oryza*, **55**(1), 126–133.

Liu, L., Waters, D. L., Rose, T. J., Bao, J., & King, G. J. (2013). Phospholipids in rice: Significance in grain quality and health benefits: A review. *Food Chemistry*, **139**(1–4), 1133–1145.

Wassmann, R., Nelson, G. C., Peng, S. B., Sumfleth, K., Jagadish, S. V. K., Hosen, Y., & Rosegrant, M. W. (2010). Rice and global climate change. In S. Pandey, D. Byerlee, D. Dawe, A. Dobermann, S. Mohanty, S. Rozelle, & B. Hardy (Eds.), *Rice in the global economy: Strategic research and policy issues for food security* (pp. 411–432). International Rice Research Institute.

Li, C., Salas, W., DeAngelo, B., & Rose, S. (2006). Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in China over the next twenty years. *Journal of Environmental Quality*, **35**, 1554–1565.

Banerjee, A., & Roychoudhury, A. (2020). Rice grain quality and abiotic stress: Genomics and biotechnological perspectives. In *Rice research for quality improvement: Genomics and genetic engineering: Volume 1: Breeding techniques and abiotic stress tolerance* (pp. 747–752). Springer.

Hasan, M. M., Rafi, M. Y., Ismail, M. R., Mahmood, M., Rahim, H. A., Alam, M. A., *et al*. (2015). Marker-assisted backcrossing: A useful method for rice improvement. *Biotechnology & Biotechnological Equipment*, **29**, 237–254. https://doi.org/10.1080/13102818.2014.995920

Bandyopadhyay, A., Kancharla, N., Javalkote, V. S., Dasgupta, S., & Brutnell, T. P. (2020). CRISPR-Cas12a (Cpf1): A versatile tool in the plant genome editing toolbox for agricultural advancement. *Frontiers in Plant Science*, **11**, 584151. https://doi.org/10.3389/fpls.2020.584151

Verma, V., Vishal, B., Kohli, A., & Kumar, P. P. (2021). Systems-based rice improvement approaches for sustainable food and nutritional security. *Plant Cell Reports*, **40**(11), 2021–2036. https://doi.org/10.1007/s00299-021-02790-6

Kadam, N. N., Xiao, G., Melgar, R. J., Bahuguna, R. N., Quinones, C., Tamilselvan, A., *et al*. (2014). Agronomic and physiological responses to high temperature, drought, and elevated CO2 interactions in cereals. *Advances in Agronomy*, **127**, 111–156.

Montzka, S. A., Dlugokencky, E. J., & Butler, J. H. (2011). Non-CO_2 greenhouse gases and climate change. *Nature*, **476**, 43–50.

Bouman, B. A. M., & Tuong, T. P. (2001). Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management*, **49**, 11–30.

Chandran, A. K. N., Sandhu, J., Irvin, L., Paul, P., Dhatt, B. K., Hussain, W. *et al*. (2022). Rice Chalky Grain 5 regulates natural variation for grain quality under heat stress. *Frontiers in Plant Science*, **13**, 1026472.

Lampayan, R. M., Samoy-Pascual, K. C., Sibayan, E. B., Ella, V. B., Jayag, O. P., Cabangon, R. J., & Bouman, B. A. M. (2014). Effects of alternate wetting and drying (AWD) threshold level and plant seedling age on crop performance, water input, and water productivity of transplanted rice in Central Luzon, Philippines. *Paddy and Water Environment*, **13**, 215–227.

Mekonnen, M. M., & Hoekstra, A. (2016). Four billion people facing severe water scarcity. *Science Advances*, **2**, 1–6.

Chan, C. C., & Nor, M. A. M. (1993). Impacts and implications of direct seeding on irrigation requirement and systems management. In *Proceedings of the Workshop on Water and Direct Seeding for Rice* (pp. 14–16). Muda Agricultural Development Authority.

Linquist, B., Anders, M. M., Adviento-Borbe, M. A. A., Chaney, R. L., Nalley, L. L., Da Roda, E. F. F., & Van Kessel, C. (2014). Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Global Change Biology*, **21**, 407–417.

Chakraborty, K., Ray, S., Vijayan, J., Molla, K. A., Nagar, R., Jena, P., *et al*. (2021). Preformed aerenchyma determines the differential tolerance response under partial submergence imposed by fresh and saline water flooding in rice. *Physiologia Plantarum*, **173**(4), 1597–1615.

Erokhin, V., Diao, L., Gao, T., Andrei, J.-V., Ivolga, A., & Zong, Y. (2021). The supply of calories, proteins, and fats in low-income countries: A four-decade retrospective study. *International Journal of Environmental Research and Public Health*, **18**(14), 7356. https://doi.org/10.3390/ijerph18147356

Pimentel, D., Berger, B., Filiberto, D. *et al*. (2004). Water resources: Agricultural and environmental issues. *BioScience*, **54**, 909–918.

Larkindale, J., Hall, J. D., Knight, M. R., & Vierling, E. (2005). Heat stress phenotypes of *Arabidopsis* mutants implicate multiple signaling pathways in the acquisition of thermo-tolerance. *Plant Physiology*, **138**, 882–897.

Jagadish, S. V. K., Cairns, J., Lafitte, R., Wheeler, T. R., Price, A. H., & Craufurd, P. Q. (2010). Genetic analysis of heat tolerance at anthesis in rice. *Crop Science*, **50**, 1633–1641. https://doi.org/10.2135/cropsci2009.09.0516

Prasad, P. V. V., Boote, K. J., Allen, L. H., Sheehy, J. E., & Thomas, M. G. (2006). Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. *Field Crops Research*, **95**, 398–411.

Liu, W., Yin, T., Zhao, Y., Wang, X., Wang, K., Shen, Y., *et al*. (2021). Effects of high temperature on rice grain development and quality formation based on proteomics comparative analysis under field warming. *Frontiers in Plant Science*, **12**, 746180.

Pathak, H., Kumar, M., Molla, K. A., & Chakraborty, K. (2021). *Abiotic stresses in rice production: Impacts and management*.

Pravallika, K., Arunkumar, C., Vijayakumar, A., Beena, R., & Jayalekshmi, V. G. (2020). Effect of high temperature stress on seed filling and nutritional quality of rice (*Oryza sativa* L.). *Journal of Crop and Weed*, **16**(2), 18–23.

Narsai, R., & Whelan, J. (2013). How unique is the low oxygen response? An analysis of the anaerobic response during germination and comparison with abiotic stress in rice and *Arabidopsis*. *Frontiers in Plant Science*, **4**, 349.

Farooq, M. A., Gao, S., Hassan, M. A., Huang, Z., Rasheed, A., Hearne, S., Prasanna, B., Li, X., & Li, H. (2024). Artificial intelligence in plant breeding. *Trends in Genetics*, **40**, 891–908.

Muthayya, S., Sugimoto, J. D., Montgomery, S., & Maberly, G. F. (2014). An overview of global rice production, supply, trade, and consumption. *Annals of the New York Academy of Sciences*, **1324**(1), 7–14. https://doi.org/10.1111/nyas.12540

Sailaja, B., Anjum, N., Vishnu Prasanth, V., Sarla, N., Subrahmanyam, D., Voleti, S. R., Viraktamath, B. C., & Mangrauthia, S. K. (2014). Comparative study of susceptible and tolerant genotype reveals efficient recovery and root system contributes to heat stress tolerance in rice. *Plant Molecular Biology Reporter*, **32**, 1228–1240.

Neglo, K. A. W., Gebrekidan, T., & Lyu, K. (2021). The role of agriculture and non-farm economy in addressing food insecurity in Ethiopia: A review. *Sustainability*, **13**(7), 3874. https://doi.org/10.3390/su13073874

Bandumula, N. (2018). Rice production in Asia: Key to global food security. *Biological Sciences*, **88**(4), 1323–1328. https://doi.org/10.1007/s40011-017-0867-7

Wallace, J. G., Rodgers-Melnick, E., & Buckler, E. S. (2018). On the road to Breeding 4.0: Unraveling the good, the bad, and the boring of crop quantitative genomics. *Annual Review of Genetics*, **52**, 421–444.

Mishra, R., Joshi, R. K., & Zhao, K. (2018). Genome editing in rice: Recent advances, challenges, and future implications. *Frontiers in Plant Science*, **9**, 1361. https://doi.org/10.3389/fpls.2018.01361

Lanning, S., & Siebenmorgen, T. (2013). Effects of preharvest nighttime air temperatures on whiteness of head rice. *Cereal Chemistry*, **90**(3), 218–222.

Das, G., & Rao, G. J. N. (2015). Molecular marker assisted gene stacking for biotic and abiotic stress resistance genes in an elite rice cultivar. *Frontiers in Plant Science*, **6**, 698. https://doi.org/10.3389/fpls.2015.00698

Samal, P., Babu, S. C., Mondal, B., & Mishra, S. N. (2022). The global rice agriculture towards 2050: An intercontinental perspective. *Outlook on Agriculture*, **51**(2), 164–172. https://doi.org/10.1177/00307270221088338

Sokra, I., Lika, R., Meta, H., Chanra, R., Linan, H., Pang, T., & Sarun, H. (2024). Extending shelf-life and preserving the quality of lady finger banana (*Musa acuminata*) via various postharvest treatments. *International Journal of Science and Research Archive*, **12**(2), 2636–2645. https://doi.org/10.30574/ijsra.2024.13.2.2460

Song, G., Jia, M., Chen, K., Kong, X., Khattak, B., Xie, C., Li, A., & Mao, L. (2016). CRISPR/Cas9: A powerful tool for crop genome editing. *Crop Journal*, **4**, 75–82.

Romero, F. M., & Gatica-Arias, A. (2019). CRISPR/Cas9: Development and application in rice breeding. *Rice Science*, **26**, 265–281.

Jeyasri, R., Muthuramalingam, P., Satish, L., Pandian, S. K., Chen, J.-T., Ahmar, S., *et al*. (2021). An overview of abiotic stress in cereal crops: Negative impacts, regulation, biotechnology and integrated omics. *Plants*, **10**, 1472. https://doi.org/10.3390/plants10071472

Kheir, E. A., Sheshshayee, M. S., Prasad, T. G., & Udayakumar, M. (2012). Temperature induction response as a screening technique for selecting high temperature-tolerant cotton lines. *Journal of Cotton Science*, **16**, 190–199.

Shah, F., Huang, J., Cui, K., Nie, L., Shah, T., & Wang, C. C. K. (2011). Impact of high-temperature stress on rice plant and its traits related to tolerance. *Journal of Agricultural Science*, **149**, 545–556.

Tabassum, J., Ahmad, S., Hussain, B., Mawia, A. M., Zeb, A., & Ju, L. (2021). Applications and potential of genome-editing systems in rice improvement: Current and future perspectives. *Agronomy*, **11**, 1359.

Xu, Y., Chu, C., & Yao, S. (2021). The impact of high-temperature stress on rice: Challenges and solutions. *Crop Journal*, **9**, 963–976.

Shi, W., Ishimaru, T., Gannaban, R. B., Oane, W., & Jagadish, S. V. K. (2015). Popular rice (*Oryza sativa* L.) cultivars show contrasting responses to heat stress at gametogenesis and anthesis. *Crop Science*, **55**, 589–596.

John, A., & Fielding, M. (2014). Rice production constraints and 'new' challenges for South Asian smallholders: Insights into de facto research priorities. *Agriculture & Food Security*, **3**(1), 18. https://doi.org/10.1186/2048-7010-3-18

Chang, S.-H.-E., Benjamin, E. O., & Sauer, J. (2024). Factors influencing the adoption of sustainable agricultural practices for rice cultivation in Southeast Asia: A review. *Agronomy for Sustainable Development*, **44**(3), 27. https://doi.org/10.1007/s13593-024-00960-w

Somaly, S., & Sokra, I. (2024). The efficacy of Bordeaux mixture and *Trichoderma* powder in preventing fungal diseases on cashew nut wounds after pruning. *Cambodian Journal of Education and STEM*, **1**(2), 79–96. https://doi.org/10.62219/cjes.2024226

Li, T., Liu, B., Spalding, M. H., Weeks, D. P., & Yang, B. (2012). High-efficiency TALEN-based gene editing produces disease-resistant rice. *Nature Biotechnology*, **30**, 390–392. https://doi.org/10.1038/nbt.2199

Shrestha, S., Mahat, J., Shrestha, J., Madhav, K. C., & Paudel, K. (2022). Influence of high-temperature stress on rice growth and development: A review. *Heliyon*, **8**, e1265.

Fahad, S., Adnan, M., Noor, M., Arif, M., Alam, M., Khan, I. A. *et al*. (2019). Major constraints for global rice production. In M. Hasanuzzaman, M. Fujita, K. Nahar, & J. K. Biswas (Eds.), *Advances in rice research for abiotic stress tolerance* (pp. 1–22). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-814332-2.00001-0

Papademetriou, M. K., Dent, F. J., & Herath, E. M. (2000). *Bridging the rice yield gap in the Asia-Pacific region*. FAO.

Prasad, R., Shivay, Y. S., & Kumar, D. (2017). Current status, challenges, and opportunities in rice production. In B. S. Chauhan, K. Jabran, & G. Mahajan (Eds.), *Rice production worldwide* (pp. 1–32). Springer International Publishing. https://doi.org/10.1007/978-3-319-47516-5_1

Feng, Z., Zhang, B., Ding, W., Liu, X., Yang, D., Wei, P. *et al*. (2013). Efficient genome editing in plants using a CRISPR/Cas system. *Cell Research*, **23**, 1229–1232. https://doi.org/10.1038/cr.2013.114

Mohd-Hanafiah, N., Mispan, M. S., Lim, P. E., Baisakh, N., & Cheng, A. (2020). The 21st century agriculture: When rice research draws attention to climate variability and how weedy rice and underutilized grains come in handy. *Plants*, **9**(3), 365. https://doi.org/10.3390/plants9030365

Kumar, N., Chhokar, R. S., Meena, R. P., Kharub, A. S., Gill, S. C., Tripathi, S. C. *et al*. (2022). Challenges and opportunities in productivity and sustainability of rice cultivation system: A critical review in Indian perspective. *Cereal Research Communications*, **50**(4), 573–601. https://doi.org/10.1007/s42976-021-00214-5

Gopalakrishnan, T., Hasan, M. K., Haque, A. T. M. S., Jayasinghe, S. L., & Kumar, L. (2019). Sustainability of coastal agriculture under climate change. *Sustainability*, **11**(24), 7200. https://doi.org/10.3390/su11247200

Somaly, S., Lika, R., Socheata, C., & Sokra, I. (2025). Effect of blanching temperature and time on the chemical properties of Keo Romeat mango (*Mangifera indica*) in Cambodia. *Journal of Agriculture and Technology*, **1**(2), 37–46. https://doi.org/10.5281/zenodo.15655777

Medeiros, A., Fernandes, C., Gonçalves, J. F., & Farinha-Marques, P. (2021). Research trends on integrative landscape assessment using indicators – A systematic review. *Ecological Indicators*, **129**, 107815. https://doi.org/10.1016/j.ecolind.2021.107815

Tahir, F., Ashfaq, H., Khan, A. Z., Amin, M., Akbar, I., Malik, H. A., *et al*. (2024). Emerging trends in algae farming on non-arable lands for resource reclamation, recycling, and mitigation of climate change-driven food security challenges. *Reviews in Environmental Science and Bio/Technology*, **23**(3), 869–896. https://doi.org/10.1007/s11157-024-09697-0

Singh, V. J., Gampala, S., Singh, A. K., & Chakraborti, S. K. (2015). DUS characterization of mega rice varieties and landraces of India. *Annals of Plant and Soil Research*, **17**(2), 156–159.

Pandey, S. (2005). Trends in crop establishment methods. In *Rice is life: Scientific perspectives for the 21st century* (p. 178).

Lemarié, S., & Marette, S. (2022). The socio-economic factors affecting the emergence and impacts of new genomic techniques in agriculture: A scoping review. *Trends in Food Science & Technology*, **129**, 38–48. https://doi.org/10.1016/j.tifs.2022.07.013

Ma, X., Zhang, X., Liu, H., & Li, Z. (2020). Highly efficient DNA-free plant genome editing using virally delivered CRISPR–Cas9. *Nature Plants*, **6**, 773–779. https://doi.org/10.1038/s41477-020-0704-5

Rizzo, G., Migliore, G., Schifani, G., & Vecchio, R. (2024). Key factors influencing farmers' adoption of sustainable innovations: A systematic literature review and research agenda. *Organic Agriculture*, **14**(1), 57–84. https://doi.org/10.1007/s13165-023-00440-7

Gava, O., Bartolini, F., Venturi, F., Brunori, G., & Pardossi, A. (2020). Improving policy evidence base for agricultural sustainability and food security: A content analysis of life cycle assessment research. *Sustainability*, **12**(3), 1033. https://doi.org/10.3390/su12031033

Weeks, D. P., Spalding, M. H., & Yang, B. (2016). Use of designer nucleases for targeted gene and genome editing in plants. *Plant Biotechnology Journal*, **14**, 483–495. https://doi.org/10.1111/pbi.12448

IPCC. (2014). *Climate change 2014: Mitigation of climate change*. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, *et al*. (Eds.), Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Nerkar, G., Thorat, A., Sheelavantmath, S., Babu, K. H., & Devarumath, R. (2018). Genetic transformation of sugarcane and field performance of transgenic sugarcane. In S. S. Gosal & S. H. Wani (Eds.), *Biotechnologies of crop improvement* (Vol. 2). Springer Nature. https://doi.org/10.1007/978-3-319-90650-8_9

Jinek, M., Chylinski, K., Fonfara, I., Hauer, M., Doudna, J. A., & Charpentier, E. (2012). A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity. *Science*, **337**, 816–821. https://doi.org/10.1126/science.1225829

Zhang, Y., Liang, Z., Zong, Y., Wang, Y., Liu, J., Chen, K., *et al*. (2016). Efficient and transgene-free genome editing in wheat through transient expression of CRISPR/Cas9 DNA or RNA. *Nature Communications*, **7**, 1–8. https://doi.org/10.1038/ncomms12617

Xu, R., Li, H., Qin, R., Wang, L., Li, L., Wei, P., *et al*. (2014). Gene targeting using the *Agrobacterium tumefaciens*-mediated CRISPR-Cas system in rice. *Rice*, **7**, 5. https://doi.org/10.1186/s12284-014-0005-6

Wang, F., Wang, C., Liu, P., Lei, P., Hao, W., Gao, Y., *et al*. (2016). Enhanced rice blast resistance by CRISPR/Cas9-targeted mutagenesis of the ERF transcription factor gene *OsERF922*. *PLoS ONE*, **11**, e0154027. https://doi.org/10.1371/journal.pone.0154027

Zhang, D., Zhang, Z., Unver, T., & Zhang, B. (2021). CRISPR/Cas: A powerful tool for gene function study and crop improvement. *Journal of Advanced Research*, **29**, 207–221.

Pandey, S. (2005). Trends in crop establishment methods. In *Rice is life: Scientific perspectives for the 21st century* (p. 178).

Pandey, S., & Velasco, L. (2002). Economics of direct seeding in Asia: Patterns of adoption and research priorities. In *Direct seeding: Research strategies and opportunities* (pp. 3–14).