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Sustainable and low-emission climate-smart rice: A review

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Abstract

Rice is a staple food crop that supports the livelihoods and food security of more than half of the world's population. However, conventional rice cultivation is increasingly threatened by climate change, water scarcity, declining natural resources, and rising greenhouse gas (GHG) emissions, particularly methane from flooded paddy fields. Climate-smart rice (CSR) cultivation has emerged as a sustainable approach to address these challenges by enhancing productivity, improving resilience to climatic stresses, and reducing the environmental footprint of rice production. This review examines the major climate-smart strategies for sustainable rice cultivation, including the adoption of climate-resilient and low-emission rice varieties, efficient organic matter management, biochar application, integrated nutrient management, subsurface nitrogen placement, biofertilizer use, alternate wetting and drying (AWD), aerobic rice cultivation, and precision irrigation technologies such as drip and smart irrigation systems. The role of digital agriculture, sensor-based irrigation, and Internet of Things (IoT)-enabled decision support systems in improving resource-use efficiency is also discussed. In addition, the review highlights the major constraints to the adoption of climate-smart rice technologies, including limited farmer awareness, inadequate infrastructure, water management challenges, increased weed pressure, high initial investment costs, and insufficient policy support. Future prospects involving advanced breeding, artificial intelligence, remote sensing, carbon credit mechanisms, and strengthened extension services are explored as pathways for scaling up climate-smart practices. The integration of these technologies and management strategies can improve water and nutrient use efficiency, reduce greenhouse gas emissions, strengthen resilience to climate variability, and ensure sustainable rice production. Successful implementation of climate-smart rice cultivation will require coordinated efforts in research, policy support, technological innovation, and farmer capacity building to achieve long-term food security and environmental sustainability.

Keywords: Climate-smart rice, climate change, greenhouse gas emissions, alternate wetting and drying, biochar, precision irrigation, climate-resilient varieties, sustainable rice production

Introduction

Rice is one of the world's most important staple food crops, providing food and nutritional security for more than half of the global population. In India, rice is the principal food grain, occupying about 40-43 per cent of the total food grain area, with nearly 52 per cent of the cultivated area being rainfed (Bhambure and Kerkar, 2016) ^[2]. India is the second-largest rice producer in the world, contributing nearly one-fifth of global rice production (Pavithra *et al.*, 2018) ^[36]. However, rice cultivation, particularly under rainfed conditions, is highly vulnerable to abiotic stresses such as drought and flooding, as well as biotic stresses including pests and diseases. Climate change has further intensified these challenges, threatening the sustainability and productivity of rice-based farming systems (NRRI, 2018). Rice cultivation is also a significant source of agricultural greenhouse gas (GHG) emissions, particularly methane, contributing substantially to global warming (Adhya *et al.*, 2014; WWF, 2022) ^[1]. Therefore, there is an urgent need for production systems that can sustain productivity while minimizing environmental impacts. Climate-smart agriculture (CSA) has emerged as a sustainable approach to address these challenges by achieving three major objectives: enhancing agricultural productivity, strengthening resilience and adaptation to climate change, and mitigating greenhouse gas emissions (FAO, 2010; Jena *et al.*, 2023) ^[17]. In rice production, climate-smart practices such as improved water and nutrient management, stress-tolerant varieties,

conservation agriculture, precision farming, integrated pest management, and crop diversification have shown considerable potential to improve resource-use efficiency, enhance profitability, and reduce the environmental footprint of cultivation (Kakraliya *et al.*, 2021) ^[19]. Considering the increasing demand for rice and the growing impacts of climate change, the adoption of climate-smart strategies has become essential for sustainable rice production. This review highlights the different strategies of climate-smart rice cultivation and their role in enhancing productivity, resilience, and environmental sustainability.

Concept of climate-smart rice

Climate-smart rice (CSR) refers to the development of climate-resilient rice varieties and the adoption of sustainable management practices aimed at enhancing productivity while reducing the environmental footprint of rice cultivation. It is also referred to as "green rice" because of its potential to reduce carbon emissions, improve water-use efficiency, and enhance resilience to climate-related stresses. Climate-smart rice integrates breeding and production strategies that emphasize low external inputs, efficient resource utilization, and tolerance to multiple biotic and abiotic stresses. climate-smart rice production encompasses several interconnected dimensions, including water-smart practices such as alternate wetting and drying (AWD) and weather-based irrigation scheduling; nutrient-smart approaches based on the 4R nutrient stewardship concept, slow-release fertilizers, subsurface nitrogen application, and site-specific nutrient management; carbon-smart practices such as residue management, biochar application, and conservation tillage; energy-smart technologies including direct-

seeded rice and laser land levelling; weather-smart interventions involving climate-resilient varieties and agro-advisory services; and knowledge-smart approaches such as precision farming and crop insurance (Das *et al.*, 2024) ^[6]. The integration of these components contributes to improved productivity, climate resilience, resource-use efficiency, and reduced greenhouse gas emissions, thereby supporting sustainable rice production.'

Strategies for climate smart rice production
Climate resilient varieties

Climate-resilient rice varieties are cultivars developed to withstand one or more climate-related stresses, including drought, submergence, salinity, heat, and pests and diseases, thereby ensuring stable productivity under changing climatic conditions. The development and adoption of such varieties are essential for sustaining rice production and enhancing the resilience of farming systems to climate change. The stress-tolerant versions of popular rice cultivars can help farming communities mitigate the impacts of recurrent flooding and drought (Nayak *et al.*, 2022) ^[31] Similarly, Suresh *et al.* (2024) ^[45] emphasized the importance of breeding climate-resilient rice varieties to meet future food demands under changing climatic conditions. A study conducted at the National Rice Research Institute, Cuttack, Odisha, demonstrated that climate-resilient varieties exhibited significant yield advantages over local cultivars under various stress conditions (Chattopadhyay *et al.*, 2016) ^[3]. The adoption of climate-resilient rice varieties is therefore a key climate-smart strategy for improving productivity, enhancing adaptation to climate variability, and ensuring long-term food security.

Table 1: Yield advanatge of different stress tolerant varieties over local cultivars

Type of stress	Rice variety	Average estimated yield (kg ha ⁻¹)	Average yield advantage (%)
Flood prone	Varshadhan	4367.29	14.54
	Check (local varieties)	3733.91	
Salinity prone	CR Dhan 403	4554.39	13.79
	Check (local varieties)	3926.04	
	CR Dhan 406	4281.38	15.00
	Check (local varieties)	3639.27	
Submergence	Swarna -Sub 1	3759.15	3.75
	Check (local varieties)	3618.28	
Overall	NRRI varieties	4240.55	11.77
	Check (local varieties)	3729.38	

(Chattopadhyay *et al.*, 2016) ^[3]

Low-emission rice varieties

Low-emission rice varieties are an emerging climate-smart strategy for mitigating greenhouse gas emissions from paddy fields while maintaining productivity. Methane (CH₄) emissions from rice cultivation are primarily produced by methanogenic archaea under the anaerobic conditions of flooded soils. These microorganisms utilize carbon compounds derived mainly from rice root exudates, which are estimated to contribute nearly 70 per cent of the methane emitted from paddy fields (Watanabe *et al.*, 1999; Khosa *et al.*, 2010) ^[21, 48]. Variations in root characteristics and exudation patterns among rice cultivars result in considerable differences in methane emission potential (King and Reeburgh, 2002 ^[23]; Lu and Conrad, 2005; Chen *et al.*,

2021) ^[4, 28]. The high-yielding, low-methane-emitting rice varieties could be considered a clean development technology with potential for carbon credit schemes (Soremi *et al.*, 2023) ^[43]. They observed that rice varieties with shorter roots and lower root volume produced lower methane emissions. Similarly, low-methane rice varieties could reduce CH₄ emissions by up to 70 per cent through reduced root exudation and enhanced sugar transport to aerial plant parts without compromising yield potential (Hu *et al.*, 2024) ^[12]. They identified Heijing 5 as a promising genotype for future low-emission rice breeding programmes. Therefore, the development and adoption of low-emission rice varieties can contribute significantly to sustainable and climate-smart rice production.

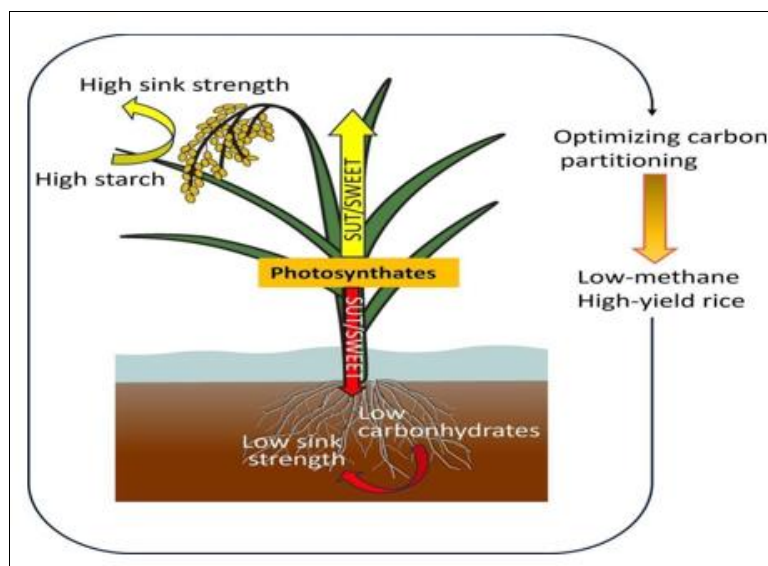


Fig 1: Graphical abstract of carbon partitioning in low emission rice. (Hu *et al.*, 2024) ^[12]

Scientific management of organic matter

Organic matter management is a key component of climate-smart rice cultivation, as it improves soil fertility and productivity, enhances resilience to climatic stresses, and mitigates greenhouse gas emissions. Appropriate management of crop residues and organic amendments can improve soil physical, chemical, and biological properties while reducing the environmental footprint of rice production. However, the continuous incorporation of rice straw into flooded paddy soils provides abundant substrates for methanogenic microorganisms and stimulates the decomposition of soil organic matter, thereby increasing CH₄ emissions under anaerobic conditions (Huang *et al.*, 2024) ^[13]. In contrast, anaerobic digestion of rice straw has emerged as a promising alternative for residue management. The anaerobic digestion not only reduces methane emissions from paddy fields but also generates renewable energy and high-quality organic fertilizers (Ni *et al.*, 2025) ^[32]. Thus, sustainable organic matter management can improve soil health while reducing greenhouse gas emissions, making it an important climate-smart strategy for rice cultivation.

Application of biochar

Biochar is a carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions (Verheijen *et al.*, 2010) ^[47]. Its application in rice cultivation has gained attention as an effective climate-smart practice for improving soil quality and reducing greenhouse gas emissions. Biochar application reduced CH₄ emissions by increasing the abundance of methanotrophic bacteria while decreasing the ratio of methanogens to methanotrophs (Feng *et al.*, 2012) ^[10]. Several studies have demonstrated that biochar amendments can reduce methane emissions by 34-91 per cent (Liu *et al.*, 2011; Kim *et al.*, 2017) ^[22, 27]. The different biochar particle sizes and observed that both sizes effectively reduced methane production and emission from anaerobic rice soils (Sriphitom *et al.*, 2020) ^[44]. The reduction was attributed to improved soil aeration, increased soil redox potential, suppression of methanogenic microorganisms, and stimulation of methanotrophic bacteria. In addition to mitigating methane emissions, biochar enhances soil fertility and carbon sequestration, making it a valuable component of climate-smart rice production systems.

Nutrient management: Judicious nutrient management is an essential component of climate-smart rice cultivation, aiming to enhance crop productivity while minimizing greenhouse gas emissions, particularly methane and nitrous oxide. Efficient nutrient management improves nutrient-use efficiency, reduces fertilizer losses, and lowers the environmental impact of rice production. The global fertilizer industry contributes approximately 2.5 per cent of global greenhouse gas emissions, with nearly 1.5 per cent resulting from fertilizer application practices (IFA, 2016). The adoption of soil- and crop-specific nutrient management practices can substantially reduce these emissions while maintaining or improving rice productivity. Climate-smart nutrient management strategies include integrated nutrient management, site-specific nutrient management, slow-release fertilizers, and improved nitrogen application techniques, which collectively contribute to sustainable and low-emission rice production.

Rational use of chemical fertilizers along with natural nutrient resources:

Integrated nutrient management, which combines organic and inorganic nutrient sources, is an effective climate-smart strategy for improving nutrient-use efficiency and reducing greenhouse gas emissions. Kumar *et al.* (2022) ^[24] demonstrated that the combined application of 50 per cent chemical fertilizer and 50 per cent vermicompost (CF50 + VC50) significantly reduced greenhouse gas emissions and global warming potential while maintaining grain yields comparable to those obtained with sole chemical fertilization. Sole vermicompost application achieved the greatest reduction in global warming potential, with up to a 70 per cent decrease compared to conventional fertilizer management. These findings highlight the potential of integrating organic and inorganic nutrient sources to enhance soil health, sustain productivity, and promote environmentally sustainable rice cultivation.

Subsurface application of nitrogen fertilizers

Subsurface nitrogen fertilization is an effective climate-smart strategy for enhancing nutrient-use efficiency, reducing greenhouse gas emissions, and improving the resilience of rice production systems. This practice minimizes nitrogen losses while ensuring a sustained nutrient supply to the crop, making it

particularly suitable for low-emission and resource-efficient rice cultivation. Urea deep placement (UDP) has been reported to increase rice yields by 28 per cent and nitrogen recovery efficiency by 167 per cent compared with conventional broadcast urea application. Furthermore, the combination of UDP with alternate wetting and drying (AWD) irrigation improved grain yield and nitrogen-use efficiency without increasing N_2O and NO emissions (Islam *et al.*, 2018) ^[15]. UDP reduced cumulative CH_4 emissions by 17-31 per cent (Islam *et al.*, 2024) ^[16]. This reduction was attributed to the prolonged retention of $\text{NH}_4^+\text{-N}$ in the subsurface soil, which promoted methane oxidation by soil methanotrophs. In addition, nitrogen placement at a depth of 8-10 cm enhanced root growth and oxygen availability in the rhizosphere, thereby increasing methane oxidation and reducing CH_4 emissions. Thus, subsurface nitrogen application contributes to enhanced productivity while mitigating greenhouse gas emissions in climate-smart rice systems.

Biofertilizers for low-emission rice production

Biofertilizers have shown considerable potential in reducing methane emissions while improving soil fertility and crop productivity. Microbial inoculants such as cyanobacteria, mycorrhizae, Azolla, and diazotrophs enhance nutrient cycling, improve soil properties, and contribute to sustainable rice production (Prasanna *et al.*, 2002; Kennedy *et al.*, 2004; Nadeem *et al.*, 2014; Singh and Strong, 2016) ^[20, 30, 37, 42]. Senthilraja *et al.* (2023) ^[40] evaluated the effects of various organic amendments on CH_4 emissions, soil redox potential, dissolved oxygen, and paddy yield. Their findings indicated that the combined application of organic amendments with blue-green algae produced higher grain yields while generating lower methane emissions than organic amendments alone. Compared with the conventional farmer practice of farmyard manure incorporation, the combined application of Azolla and blue-green algae effectively maintained lower CH_4 emissions. These findings highlight the potential of biofertilizers as an eco-friendly and climate-smart approach for sustainable rice cultivation.

Smart water management practices

Efficient water management is a fundamental component of climate-smart rice cultivation, aiming to reduce water consumption and greenhouse gas emissions while sustaining crop productivity. Water-saving practices such as alternate wetting and drying (AWD) and mid-season drainage create alternating aerobic and anaerobic soil conditions that suppress methane production without adversely affecting grain yield. These practices improve water-use efficiency and reduce the environmental footprint of rice cultivation.

Alternate wetting and drying

Alternate wetting and drying (AWD) is a water-saving irrigation technique that involves periodic drying and re-flooding of paddy fields instead of maintaining continuous flooding. AWD reduces irrigation water requirements and suppresses soil methanogenesis, thereby lowering methane emissions from rice fields (Dahlgreen and Parr, 2024) ^[5]. Echegaray-Cabrera *et al.* (2024) ^[8] evaluated several AWD irrigation regimes and compared them with continuous flooding. Their results demonstrated that AWD effectively reduced greenhouse gas emissions while conserving irrigation water. These findings emphasize that AWD is an important climate-smart practice capable of improving water-use efficiency and reducing the environmental impact of rice cultivation.

Aerobic rice cultivation practices

Aerobic rice is a production system in which rice is cultivated under well-drained, non-puddled, and non-flooded soil conditions, similar to upland crops. This system is designed to reduce irrigation water requirements and lower greenhouse gas emissions, particularly methane. Methane emissions from flooded rice paddies are a major source of atmospheric CH_4 and represent a significant greenhouse gas with high climate-forcing potential due to anthropogenic activities globally (Lee *et al.*, 2024) ^[26]. Aerobic rice cultivation can reduce irrigation water use by approximately 50 per cent compared with conventional lowland rice systems. Aerobic rice offers a promising solution to increasing water scarcity in both present and future production scenarios (Dey *et al.*, 2018) ^[7]. The superiority of aerobic rice in mitigating GHG emission from rice fields was revealed from the significantly lower efflux of CH_4 under aerobic ($3.03 \text{ mg m}^{-2} \text{ h}^{-1}$) compared to flooded rice ($6.16 \text{ mg m}^{-2} \text{ h}^{-1}$) (Jinsy V.S., 2014) ^[18]. In addition, aerobic rice minimizes water losses through evaporation, seepage, and deep percolation, thereby improving overall water productivity (Silwal *et al.*, 2020) ^[41]. Consequently, aerobic rice cultivation represents an important climate-smart strategy for sustainable rice production in water-limited environments.

Climate-smart precision irrigation

Precision irrigation involves the use of advanced technologies to apply water and nutrients according to crop requirements, thereby maximizing resource-use efficiency and minimizing wastage. This approach is increasingly important for sustainable rice production under changing climatic conditions and increasing water scarcity.

Drip irrigation in rice

Drip irrigation is an innovative water-saving technology that has shown considerable potential in direct-seeded and aerobic rice cultivation. Studies have demonstrated that water productivity under drip irrigation is significantly greater than under conventional flooded rice systems because of reduced evaporation, seepage, runoff, and deep percolation losses. Precise water application through drip irrigation improves root activity, canopy photosynthesis, and dry matter partitioning, resulting in nearly a two-fold increase in water productivity in aerobic rice systems (Parthasarathi *et al.*, 2018) ^[34]. Drip irrigation reduced methane emissions while improving rice growth and grain yield compared with conventional aerobic cultivation practices (Parthasarathi *et al.*, (2019) ^[35]. Therefore, drip irrigation is a promising climate-smart technology for improving water productivity and reducing greenhouse gas emissions.

Smart irrigation

Smart irrigation integrates advanced technologies such as soil moisture sensors, the Internet of Things (IoT), wireless communication networks, weather stations, remote sensing, satellite imaging, and cloud computing to optimize irrigation scheduling. These technologies provide real-time information on crop water requirements and enable precise water management. Morchid *et al.* (2024) ^[29] highlighted the contribution of smart irrigation systems to water and food security through advanced agricultural technologies. Automated irrigation systems improve water-use efficiency by supplying water according to crop requirements (Tiwari *et al.*, 2019) ^[46]. Kumar *et al.* (2024) ^[25] developed a sensor-based automated irrigation system for rice cultivated under the AWD technique that effectively regulates

water levels and minimizes water wastage. The integration of digital technologies with irrigation management has significant potential to enhance resource-use efficiency and promote sustainable climate-smart rice production.

Table 2: Comparative effect of climate-smart rice management practices on greenhouse gas emissions and global warming potential

Rice management practice	CH ₄ Emission	N ₂ O Emission	Overall GWP	Major advantage	Key reference(s)
Continuous flooding	High	Low	High	Conventional practice; stable water supply	Qian <i>et al.</i> (2023) ^[38]
Alternate wetting and drying (AWD)	Low	Moderate	Low	Reduces methane and saves irrigation water	Echegaray-Cabrera <i>et al.</i> (2024) ^[8]
Aerobic rice	Very low	Moderate	Low	Large water savings and reduced methane production	Selvaraj and Ramesh (2020) ^[39]
Drip irrigation	Low	Slight increase	Low	Improved water productivity and reduced GHG emissions	Parthasarathi <i>et al.</i> (2019) ^[35]
System of Rice Intensification (SRI)	Moderate reduction	Slight increase	Low	Higher productivity with lower environmental footprint	Hasanah <i>et al.</i> (2019) ^[11]
Precision irrigation (sensor-based)	Low	Stable	Low	Automated water management and enhanced resource-use efficiency	Xiao <i>et al.</i> (2025) ^[50]

Challenges in climate-smart rice cultivation

Climate-smart rice cultivation offers significant benefits but faces several challenges that limit its adoption. Limited farmer awareness, dependence on traditional practices, and inadequate access to technologies such as smart irrigation and digital tools hinder implementation. Water management difficulties, especially under unpredictable rainfall and poor irrigation infrastructure, further constrain practices like alternate wetting and drying (AWD). A major challenge in AWD and aerobic rice systems is increased weed infestation due to periodic soil drying, necessitating effective integrated weed management. Although AWD reduces methane (CH₄) emissions, it may increase nitrous oxide (N₂O) emissions of nitrogen fertilizers are poorly managed, highlighting the need for integrated water and nutrient management. Additional constraints include limited policy support, inadequate extension services, high initial investment costs, lack of specialized machinery for direct-seeded rice (DSR), soil suitability issues, and uncertainties regarding economic returns. Addressing these challenges requires coordinated efforts in policy, farmer education, technological innovation, and infrastructure development.

Future prospects

Climate-smart rice cultivation has strong potential to enhance sustainability, resource-use efficiency, and food security under changing climatic conditions. Practices such as alternate wetting and drying (AWD), direct-seeded rice (DSR), aerobic rice, and climate-resilient varieties are expected to play a key role in future rice production. The integration of advanced technologies, including the Internet of Things (IoT), artificial intelligence (AI), remote sensing, and soil moisture sensors, will improve precision in water and nutrient management. Continued advances in rice breeding are likely to develop varieties with greater tolerance to drought, flooding, heat, and salinity. Increased policy support, financial incentives, extension services, and carbon credit initiatives can further promote the adoption of climate-smart practices. In the long term, these innovations are expected to improve productivity, reduce production costs and greenhouse gas emissions, strengthen resilience to climate change, and contribute to sustainable food and environmental security.

Conclusion

Climate-smart rice (CSR) cultivation offers a sustainable pathway to enhance rice productivity while addressing the challenges of climate change, water scarcity, and greenhouse gas

emissions. The successful implementation of CSR relies on an integrated approach involving climate-resilient varieties, efficient water and nutrient management, residue management, and precision farming technologies. Emerging tools such as weather-based agro-advisories, smart irrigation, and digital agriculture can further improve resource-use efficiency and farm resilience. However, the widespread adoption of CSR requires strong policy support, investment in research and infrastructure, effective extension services, and regular farmer training programs. Collaborative efforts among researchers, policymakers, and farming communities are essential to promote climate-smart technologies, ensuring long-term food security, environmental sustainability, and improved livelihoods for small and marginal farmers.

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