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Review of Adaptation and Mitigation Practices in Rice Farming under a Climate-Smart Agriculture Framework

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Abstract

This article synthesizes key adaptation and mitigation practices in rice farming through a Climate-Smart Agriculture (CSA) lens, with particular emphasis on water management, crop and soil management, nutrient and residue management, and integrated pest management.

Introduction

Climate-Smart Agriculture (CSA) is an integrated approach to agricultural system management that seeks to sustainably increase productivity, enhance resilience and adaptive capacity to climate variability, and reduce or remove greenhouse gas (GHG) emissions (FAO, 2013). Rice-based systems are central to global food security but are also among the most climate-sensitive agricultural systems and a major source of methane emissions within agriculture. As climate change intensifies water scarcity, temperature extremes, and pest pressures (IPCC, 2022), transforming rice farming systems has become a priority for both adaptation and mitigation strategies.

This paper is structured as follows. The first section examines practices within rice production systems that enhance resilience while reducing emissions. The second section highlights the need to integrate these practices into national policy and climate frameworks. The final section presents the conclusions.

1. Adaptation and Mitigation Pathways

Optimizing water management, deploying improved crop varieties, implementing precision nutrient management, applying biochar, promoting diversified cropping systems, improving tillage and residue management, and integrating crop–livestock systems have demonstrated substantial potential to simultaneously support climate change mitigation and adaptation (Mbow et al., 2019).

1.1. Water Management

Water management is a critical lever for integrating mitigation and adaptation in rice systems. Reducing flooding duration lowers methane emissions while enhancing drought resilience and increasing management flexibility under variable water availability.

1.1.1. Alternate Wetting and Drying (AWD)

Alternate Wetting and Drying (AWD) is a water management practice in irrigated rice systems whereby fields are allowed to dry to a predefined soil moisture threshold before re-irrigation. By reducing the duration of anaerobic soil conditions that favor methane production, AWD is widely recognized as an effective mitigation strategy. Empirical evidence indicates that AWD can significantly reduce methane emissions while conserving water and maintaining yields in irrigated lowland rice systems (IRRI, 2013; Lampayan et al., 2015).

1.1.2. Irrigation Efficiency

Improving irrigation efficiency is a cornerstone of climate-smart rice production. Enhanced control over irrigation timing, distribution, and volume reduces non-productive water losses and creates soil conditions less conducive to prolonged anaerobic decomposition, thereby lowering methane emissions (FAO, 2013; Arenas-Calle et al., 2022).

Intermittent flooding offers a transitional approach in contexts where continuous flooding remains prevalent. By periodically reducing surface water levels while maintaining adequate soil moisture, this practice lowers methane emissions relative to permanent flooding without compromising weed control or yield stability (IPCC, 2019; Loaiza et al., 2025).

Investments in improved drainage infrastructure further enhance irrigation efficiency by enabling the rapid removal of excess water following rainfall or irrigation events. From both adaptation and mitigation perspectives, effective drainage improves root aeration, reduces waterlogging stress, and limits extended anaerobic soil conditions (Minamikawa, 2025).

Emerging irrigation technologies, such as sensor-based automated irrigation, drip irrigation, and sprinkler systems, are increasingly relevant for rice production. These technologies improve precision and spatial control of water application, reduce overall water use, and support yield stability under water-scarce conditions (Arouna et al., 2023; Kumar et al., 2024; Spanu et al., 2024).

1.1.3. Land Leveling

Land leveling, particularly variable-slope smoothing, improves irrigation uniformity and drainage while minimizing soil disturbance and earth movement. By eliminating surface depressions, land leveling reduces waterlogging, shortens irrigation cycles, and lowers overall water consumption (Bueno et al., 2020). These benefits support adaptation through improved water control under variable rainfall and mitigation by facilitating intermittent flooding and drainage practices that reduce methane emissions (Nguyen-Van-Hung et al., 2022).

1.2. Crop, Soil, Nutrient, and Pest Management Practices

1.2.1. Cultivar Selection and Breeding

Rice cultivars differ significantly in traits influencing methane emissions, including growth duration, biomass production, and root system architecture (Li et al., 2022; Soremi et al., 2023). The adoption of improved genotypes with optimized root morphology and shorter growth cycles has been shown to reduce methane emissions and emission intensity (Tran et al., 2025).

Modern breeding programs increasingly prioritize tolerance to heat, drought, salinity, and pests, thereby strengthening adaptive capacity while sustaining productivity under climate stress (FAO, 2013; Mbow et al., 2019).

1.2.2. Crop Rotation and Integrated Systems

Crop rotation, particularly the alternation of rice with upland crops such as legumes or maize, disrupts continuous monocropping, improves soil fertility, and reduces water demand relative to flooded rice systems (Reddy, 2024).

Integrated rice-based systems, including rice–fish, rice–livestock, and rice–agroforestry systems, further enhance resilience by improving nutrient cycling, diversifying income sources, and strengthening food and nutrition security (Russelle et al., 2007; Roshetko et al., 2018; Gutty, 2024; Hoque et al., 2025).

1.2.3. Residue Management

Rice residues, when incorporated into soil or composted, enhance soil organic carbon stocks and nutrient cycling while avoiding emissions associated with open-field burning. Although straw incorporation under flooded conditions can increase methane emissions, practices such as pre-decomposition or composting prior to application substantially mitigate this effect (Song et al., 2019; Tran et al., 2025). Alternative uses of rice residues for bioenergy, animal feed, or mushroom

cultivation provide additional low-carbon utilization pathways (Gummert et al., 2020).

1.2.4. Soil Preparation and Amendments

Reduced or zero tillage conserves soil organic carbon, improves soil structure, reduces erosion, and lowers fuel-related CO_2 emissions from machinery use (FAO, 2013).

Microbial interventions and biochar application have emerged as promising approaches to regulate soil biogeochemical processes, reduce methane emissions, and improve nutrient-use efficiency, while simultaneously enhancing yields and system resilience (Tran et al., 2025).

1.3. Nutrient Management

Optimized nutrient management, focusing on fertilizer type, timing, placement, and application rates, enhances yields while reducing nitrous oxide emissions and overall GHG intensity (Linquist et al., 2012; Li et al., 2021; Chen et al., 2024). Site-specific nutrient management further strengthens plant vigor and improves tolerance to climate-related stresses (Chaudhary et al., 2025).

1.4. Integrated Pest Management

Integrated Pest Management (IPM) combines preventive, biological, cultural, and selective chemical strategies to control pests while minimizing environmental and health impacts (Pretty & Bharucha, 2015). By reducing reliance on chemical pesticides, IPM contributes indirectly to mitigation while enhancing system resilience through improved pest and disease management (FAO, 2024).

2. Aligning Practices with National Climate Commitments

Integrating practices that simultaneously support adaptation and mitigation into national climate commitments, adaptation plans, and sectoral mitigation strategies is essential to ensure policy coherence and enhance effectiveness. While such practices are often framed as general best-practice recommendations for agriculture, their transformative potential is substantially strengthened when translated into concrete, measurable, and reportable commitments—for example, Nationally Appropriate Mitigation Actions (NAMAs) for rice systems embedded within Nationally Determined Contributions (NDCs).

For effective implementation and scaling, field-level actions must be operationalized through clearly defined indicators, such as kg CH_4 ha^{-1}, kg N_2O ha^{-1}, m^3 of irrigation water ha^{-1}, implemented area (ha), and grain yield (t ha^{-1}), that enable robust monitoring, reporting, and verification. This approach bridges the gap between policy objectives and on-farm implementation, ensures consistency across adaptation and mitigation agendas, and reinforces the credibility of agricultural contributions to national climate strategies

Conclusions

Climate-smart practices in rice farming offer strong synergies among adaptation, mitigation, and productivity objectives. For effective implementation and scaling, these practices must be translated into measurable and reportable indicators. Aligning farm-level actions with national climate commitments enhances the contribution of rice systems to climate-resilient and low-emission agricultural development.

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