



Climate-smart water management in rice paddies: a meta-synthesis on greenhouse gas emissions and yield impacts

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Abstract

Water management practices in rice paddies, particularly alternate wetting and drying and midseason drainage followed by intermittent irrigation, are widely recognized for reducing methane (CH₄) emissions and irrigation water use compared to continuous flooding (CF). However, these practices also increase nitrous oxide (N₂O) emissions and their effect on rice yield remains unclear, especially in the context of technology dissemination to farmers. This study (1) reviews 11 recent meta-analyses on CH₄ and N₂O emissions and rice yield and (2) synthesizes their reported effects on rice growth and yield. Aggregated data show that CH₄ emissions decreased by 31–62% ($n = 10$), while N₂O emissions increased by 37–445% ($n = 7$), relative to CF. Rice yield change ranged from –5.4% to +11% with a mean of +1.3% ($n = 8$). The impact of water management on rice yield varied depending on the timing and intensity of drainage events, with excessive water stress—particularly during the heading stage—and prolonged reductive soil conditions being key risk factors. Results indicate that mild-intensity drainage practices, such as ‘safe AWD,’ not only avoid yield penalties but can significantly enhance rice productivity when tailored to favorable environmental and agronomic conditions. For effective dissemination of these practices, leveraging yield improvement as an incentive for farmers is essential. Optimizing drainage schedules in accordance with rice physiological stages and local conditions is critical. With appropriate localization, water management can serve as a climate-smart strategy that simultaneously improves water efficiency, reduces greenhouse gas emissions, and maintains or increases rice productivity.

Keywords Climate-smart agriculture · Methane · Multiple drainage · Nitrous oxide · Soil · Technology dissemination

Introduction

Methane (CH₄) is produced by methanogenic archaea using labile organic carbon (C) as a substrate in flooded paddy soils under strictly reductive conditions. Its emissions to the atmosphere result from CH₄ production, oxidation, and transport processes (Qian et al. 2023). Nitrous oxide (N₂O) emissions mainly result from microbial nitrification and denitrification in soil. Because the global warming potential (GWP) of CH₄ emissions is much higher than that of N₂O emissions in rice paddies compared to upland crops (Linguist et al. 2012), CH₄ is the greenhouse gas (GHG) that should be prioritized for mitigation in rice paddies to address climate change.

Management of organic matter (manure and rice straw) and irrigation water are the most important drivers of CH₄ emissions from rice paddies (Qian et al. 2023). While organic amendments enhance soil C sequestration and fertility, the availability of livestock manure is often limited in intensive rice-growing areas of developing countries. Furthermore, the flexibility to manage harvested rice straw is constrained by the water regime and length of the fallow period, national regulation (e.g., bans on field burning), and competing off-field uses. In contrast, water management practices involving multiple drainage events, such as alternate wetting and drying (AWD) and midseason drainage followed by intermittent irrigation (MiDi) (Minamikawa et al. 2021), are feasible in irrigated rice areas worldwide and are considered cost-effective among agricultural climate change mitigation options (Escobar Carbonari et al. 2019; Sapkota et al. 2019).

Currently, paddy water management has entered the stage of technological dissemination to farmers, supported by national initiatives and international cooperation

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aimed at achieving the Nationally Determined Contributions (NDCs). Farmers' voluntary adoption—motivated by water savings (Tirtalistyani et al. 2022), reduced costs for pump irrigation (Yamaguchi et al. 2017), and increased rice yield (Yamaguchi et al. 2017)—further accelerates the dissemination. Numerous meta-analyses spanning a wide range of spatial scales have been published to date, examining the impacts of water management on soil GHG emissions, rice grain yield, and field water use (Linguist et al. 2012; Feng et al. 2013; Carrijo et al. 2017; Guo et al. 2017; Kajiura et al. 2018; Tirol-Padre et al. 2018; Jiang et al. 2019; Liu et al. 2019; Livsey et al. 2019; Liao et al. 2021; Bo et al. 2022; see Table 1). However, reexamination of these results is necessary for appropriate interpretation in the above context. Moreover, farmers' concerns about yield loss due to water stress remain a bottleneck in the dissemination process. While recent studies (e.g., Qian et al. 2023; Lou et al. 2024) have advanced understanding of integrated GHG mitigation strategies, few have systematically reviewed the dissemination barriers from a yield perspective, especially in relation to drainage intensity and timing. Therefore, to better understand water management as a climate-smart agricultural practice, this study reviews the 11 aforementioned meta-analyses and provides a narrative synthesis of their reported positive and negative effects on rice growth and yield. It should be noted that a second-order meta-analysis is beyond the scope of this study.

An aggregation of meta-analyses on GHG emissions and rice yield

Among the aforementioned meta-analyses, CH₄ emission reduction rates achieved by water management practices, such as AWD and MiDi, compared to continuous flooding (CF)—which is typically considered the baseline—ranged from 31 to 62% with a mean and median of 50.9% and 52.7%, respectively ($n = 10$; Table 1). The relatively low reduction rates observed in Japan (39%, $n = 43$, Kajiura et al. 2018) and Southeast Asia (31%, $n = 20$, Tirol-Padre et al. 2018) were mainly due to the inclusion of field data reflecting only a single drainage practice (i.e., midseason drainage in Japan) and data collected during the wet season. Furthermore, mismatches between the timing of drainage events and the temporal peaks of CH₄ emissions can result in negligible reduction (Kajiura et al. 2018). In contrast, the relatively high reduction rates reported in China (62%, $n = 8$, Feng et al. 2013) and globally (59%, $n = 344$ Liao et al. 2021), based on data from Asia, the Americas, and Europe, were partially attributed to the inclusion of field data from practices involving more intensive drainage. Although raw data were often reused across meta-analyses, the aggregated results suggest that proper implementation of water management practices can reduce CH₄ emissions by at least 50% compared to CF. This rate is comparable to or a bit higher than the IPCC's latest scaling factor for multiple drainage periods in irrigated systems (45% reduction; error range:

Table 1 Summary of recent meta-analyses on the effect of water management practices on CH₄ and N₂O emissions, rice yield, and water use compared to continuous flooding

References	Scale	CH ₄	N ₂ O	GWP ^a	Rice yield	Water use ^b
Bo et al. (2022)	Global	− 54.2% (459)	+ 92.0% (325)	− 56.2% (309)	+ 0.4% (548)	− 39.7% (208)
Carrijo et al. (2017)	Global				− 5.4% (524)	− 25.7% (451)
Feng et al. (2013)	China	− 62% (8)	+ 278% (8)	− 54% (8)	+ 11% (8)	
Guo et al. (2017)	China	− 57% ^c (62)			+ 11% ^c (62)	
Jiang et al. (2019)	Global	− 53% (180)	+ 105% (122)	− 44% (128)	− 3.6% (160)	
Kajiura et al. (2018)	Japan	− 39% (43)				
Liao et al. (2021)	Global	− 59% (344)	+ 58% (249)	− 48% (270)	− 4.2% (347)	
Linguist et al. (2012)	Asia	− 49.5% (7)	+ 445% (7)	− 33.6% (7)	+ 0.95% ^{ns} (7)	
Liu et al. (2019)	Global	− 52.4% (70)	+ 242% (45)	− 46.6% (31)	+ 0.9% ^{c, ns} (61)	
Livsey et al. (2019)	Asia	− 52.3% (16)	+ 37.0% (16)			
Tirol-Padre et al. (2018)	Asia	− 31% (20)				

In parentheses, the number of observations (i.e., rice seasons)

Significant figures reflect the precision of values reported in the original sources

All reported percentages were statistically significant at $p < 0.05$, except for ns, nonsignificant

^a CO₂-equivalent emissions for CH₄ + N₂O calculated using the metrics in Forster et al. (2007), except for Bo et al. (2022) using Forster et al. (2021)

^b Bo et al. (2022) compared irrigation water while Carrijo et al. (2017) irrigation and rainfall water

^c Data converted by a digitizer (OriginPro 2022, OriginLab, Northampton, MA, USA)

28–59% reduction) (IPCC 2019). It should be noted that CH_4 reduction rates observed in farmers' fields may differ from those in experimental fields. Experimental data typically reflect ideal conditions with strict control over surface water levels, which may potentially lead to overestimation when extrapolated to national inventories or applied under field-based monitoring, reporting, and verification (MRV) schemes. Additionally, while both the number and intensity of drainage events are useful predictors of CH_4 emission reduction (Jiang et al. 2019), some studies have shown that a single, high-intensity drainage event may sufficiently suppress subsequent CH_4 emissions without the need for additional drainage (e.g., Haque et al. 2016; Perry et al. 2022). As noted earlier, the effectiveness of drainage timing, frequency, and intensity in reducing CH_4 emissions partly depends on when peak emissions occur under CF conditions, which are influenced by environmental and agronomic conditions (Qian et al. 2023).

The increase in N_2O emissions due to water management practices varied widely, ranging from 37 to 445% with mean and median values of 180% and 105%, respectively ($n=7$; Table 1). This finding reaffirms the trade-off between reduced CH_4 and increased N_2O emissions induced by water management practices. However, the highest increase observed in East, South, and Southeast Asia (445%, $n=7$, Linquist et al. 2012) was likely exaggerated by the inclusion of field data involving high synthetic N fertilizer application rates—specifically, up to 479 kg N ha^{-1} in China. In contrast, the lowest increase, reported for East and Southeast Asia (37.0%, $n=16$, Livsey et al. 2019), was partly due to the inclusion of field data in which N_2O emissions were already relatively high under CF conditions as a result of high N input. Although the basal incorporation of slow-release N fertilizers is effective in mitigating N_2O emissions even under water management practices (Ji et al. 2013; Wang et al. 2016), such enhanced-efficiency fertilizers remain expensive and are not yet widely accessible in all rice-producing countries. Urea topdressing immediately before or during a drainage event can significantly increase N_2O emissions (Kritee et al. 2018), which is a primary reason for the considerable N_2O emissions reported during drainage periods in previous studies. To reduce these N_2O peaks, maintaining flooded conditions for several days during and after fertilization is recommended (Samoy-Pascual et al. 2019) although this may negatively affect farmers' field operations.

The contribution of N_2O to the GWP (i.e., carbon dioxide (CO_2)-equivalent emissions) of $\text{CH}_4 + \text{N}_2\text{O}$ is generally low (i.e., typically <5%), except under extreme or poorly managed conditions. This is supported by the current aggregation, which indicates that GWP reduction rates achieved by water management practices (ranging from 33.6 to 56.2%, with mean and median values of 47.1% and 47.3%,

respectively; $n=6$; Table 1) are comparable to or slightly lower than those of CH_4 emissions alone. However, when considering the GWP of $\text{CH}_4 + \text{N}_2\text{O} + \text{CO}_2$, there is concern that water management practices may promote aerobic decomposition of soil organic C (SOC). Although temporary drainage events substantially increase CO_2 emissions during the rice-growing season (Nishimura et al. 2015), this increase can be offset by lower CO_2 emissions from residual SOC during the following dry fallow period. Nevertheless, a decade-long paddy-upland rotation study has shown that extended total drainage periods lead to greater SOC decomposition (Nishida 2016). Therefore, the impact depends on the duration and frequency of drainage, and long-term field experiments under various rice cropping systems are required to fully assess the net effect of water management practices on SOC loss.

Even though rice can be grown in continuously flooded soils, such conditions are not always optimal for its growth and resulting yield. Rice yield can be positively, negatively, or not affected by water management practices, and the rates of change ranged from -5.4 to $+11\%$ with a mean and median of $+1.3$ and $+0.7\%$, respectively ($n=8$; Table 1). These small changes are often statistically insignificant and tend to be overlooked in field studies due to the considerable spatial variability in rice yield, particularly under the direct sowing system. Noticeable yield increases were found in two studies focused on China (11%, $n=8$, Feng et al. 2013 and 11%, $n=62$, Guo et al. 2017). In contrast, although water management practices substantially reduce water use (Table 1) and improve water productivity (e.g., Phoeurn et al. 2024), Carrijo et al. (2017) reported a global mean yield loss of 5.4% ($n=524$), based on data from Asia, the Americas, Australia, Africa, and the Middle East. This figure is frequently cited as evidence of the potential risk of yield reduction from water management practices. However, this observed loss has been attributed to the inclusion of data involving water management practices with soil water potential below -20 kPa , which was often applied as an extreme experimental treatment in earlier studies (Belder et al. 2005; Bueno et al. 2010; Zhang et al. 2010; Sudhir-Yadav et al. 2011). Carrijo et al. (2017) also found that rice yield was generally not significantly reduced under conditions where soil water potential was $\geq -20 \text{ kPa}$ or when surface water levels did not fall more than 15 cm below the soil surface. The latter threshold aligns with the recipe for the safe AWD proposed by the International Rice Research Institute (IRRI) (see Allen and Sander (2019) for details). Hereafter, this study define these two thresholds as representing 'mild' drainage intensity, with more severe conditions classified as 'severe' (i.e., $< -20 \text{ kPa}$ or $> 15 \text{ cm}$ from the soil surface), and less stringent ones 'weak.' Similarly, the global mean yield loss of 3.6% ($n=160$) reported by Jiang et al. (2019), based on data from Asia, the Americas, and Europe, was also

linked to the inclusion of severe drainage data. Therefore, consistent with Mote et al. (2022), this study concludes that significant rice yield losses are unlikely under mild-intensity water management practices, such as safe AWD. As farmers are unlikely to adopt water management practices that may reduce yields, the absence of a yield penalties should be regarded as a minimum requirement for the adoption of such practices as part of climate-smart agriculture.

Strategies for improving rice yield through water management

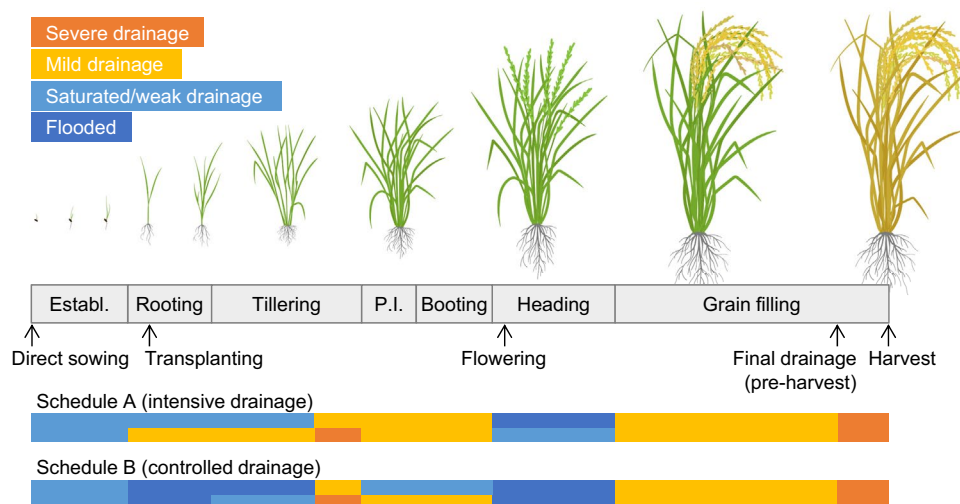
An increase in rice yield represents one of the most compelling and tangible incentives for farmers to adopt new technologies, including improved water management practices. For example, this incentive can facilitate the construction and operation of irrigation and drainage facilities (Yamaguchi et al. 2019), thereby accelerating the voluntary dissemination of water management practices (Minamikawa et al. 2019). This prompts the question: What specific characteristics of water management practices contribute to enhanced rice yield? Rice yield is influenced by multiple factors, such as soil fertility, weather conditions, rice variety, nutrient management, and pest pressure. Therefore, it is unlikely that a single mechanism triggered by water management practices can fully explain the observed yield increases. Specifically, water management practices simultaneously influence multiple aspects of rice physiology depending on the timing (i.e., growth stage) and intensity of drainage events. This study examines the effects on rice growth and yield, organized by growth stage.

After seedling establishment, CF is recommended as a protective measure against adverse weather conditions during the rooting stage (Fig. 1). At this stage, a major concern is that rice straw incorporation prior to planting may lead to the transient production and accumulation of organic

acids, as well as microbial N immobilization in flooded soils, thereby inhibiting initial rice growth (Ponnamperuma 1984). This situation is often unavoidable in multiple rice cropping systems with short fallow periods. Therefore, mild drainage during the rooting stage is desirable to address this issue (Fig. 1), as reported by Cheng (1984) and Kobayashi et al. (2000). However, plant growth may recover after the initial inhibition, and the accumulation of organic acids can also suppress weed emergence (Nozoe et al. 2022). Therefore, whether the overall impact of temporary organic acid accumulation and N immobilization on rice growth and yield is negative or positive depends on environmental and agronomic conditions. It should be noted that the early onset of drainage events is effective in mitigating the temporary CH_4 emission peak caused by straw incorporation immediately prior to planting (Samoy-Pascual et al. 2019).

Midseason drainage is a common practice in East Asia and it has a long history in this region. This practice is carried out during the late tillering stage by intentionally draining surface water for approximately 7 days, depending on the weather conditions, until cracks appear on the soil surface (Fig. 1). This practice is regarded as a single drainage with mild to severe drainage intensity. Midseason drainage has several positive effects on rice growth and yield (Minamikawa et al. 2019). First, it removes non-productive (excessive) tillers and prevents over-luxuriant growth caused by excess N uptake, thereby strengthening the remaining productive tillers and increasing their proportion. However, it can also promote N mineralization from soil organic matter. Which process becomes dominant therefore depends on the inherent soil fertility and the N fertilizer application rate. Second, it prevents canopy lodging by inhibiting the elongation of the lower internodes of the remaining tillers. Third, it promotes healthy root development by supplying oxygen to the drained soil and reducing toxic substances, such as organic acids and hydrogen sulfide. Although midseason

Fig. 1 Two alternative schedules for water management practices based on drainage intensity and rice growth stage. Color bars represent the recommended flexibility of drainage intensity for each stage. Establ., seedling establishment; P.I., panicle initiation



drainage has been shown to increase rice yields in East Asia (e.g., Back et al. 1997; Mori et al. 2003), its effectiveness is less frequently reported in other regions (e.g., Perry et al. 2022; Dossou-Yovo et al. 2023), highlighting the need for more region-specific configurations of this practice.

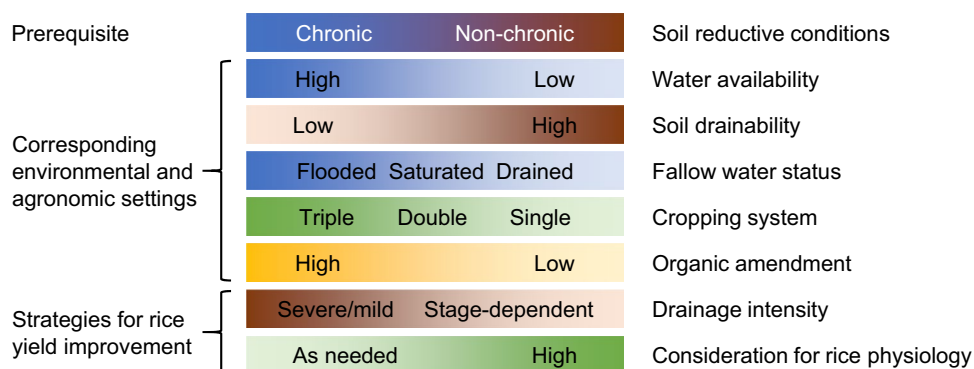
From the panicle formation to the booting stage, water management practices with weak to mild drainage intensity are recommended (Fig. 1). In Japan, intermittent irrigation—typically following midseason drainage (collectively referred to as MiDi)—is conducted to maintain healthy root development and prevent the senescence of lower leaves until the final drainage before harvest, except during the heading stage (Minamikawa et al. 2019). For farmers, a weekly management cycle—such as 4-day flooding followed by 3-day natural drainage—is commonly adopted as a guideline for intermittent irrigation. During the heading stage, rice exhibits high water demand, and elevated temperatures can induce spikelet sterility (Matsui et al. 2001, 2021). CF is therefore recommended as a protective measure in this stage, particularly at flowering (Fig. 1). However, weak drainage events may be permitted if careful attention is paid to rice water uptake (Fig. 1). For example, Tsujimoto et al. (2021) reported that a 20-day intentional drainage during and around the flowering stage significantly reduced rice yields by 13–26% during the dry season in northern Ghana; however, a similar effect was not observed during the wet season.

Grain filling is the final stage of rice growth and depends on nutrients from two sources: current assimilates and those redistributed from reserve pools in vegetative tissues (Yang and Zhang 2010). Water stress during the grain filling stage induces early senescence, reduces photosynthesis, and shortens the grain filling period, while enhancing the remobilization and transfer of pre-stored assimilates from vegetative tissues to the grain (Yang and Zhang 2006). Intentional drainage events with mild drainage intensity during this stage can increase rice yields (e.g., Yang and Zhang 2010; Li et al. 2016) (Fig. 1). Post-flowering drainage has been reported to improve rice yield by inducing phytohormonal regulation of enzymes responsible for carbon remobilization

and carbohydrate metabolism in grains (Yang and Zhang 2006, 2010). The intermittent irrigation of MiDi and the safe AWD at this stage may exert the above-mentioned effects on rice yield. However, further investigation into rice physiological responses to water stress—such as hormonal regulation mechanisms and their relationships with rice yield components—is needed, as noted by Yang and Zhang (2010).

Water management practices should be adjusted in accordance with specific environmental and agronomic conditions to optimize rice yield (Fig. 2). Under the triple rice cropping system in the Mekong Delta, Vietnam, rice yield was significantly increased by AWD relative to CF (Arai et al. 2021; Uno et al. 2021). Arai et al. (2021) reported that safe AWD increased the mean rice yield by 8.9% over a 5-year experiment conducted at a single site. This improvement was primarily attributed to enhanced nutrient translocation. Uno et al. (2021) reported that AWD increased the mean rice yield by 22% over 2-year experiments conducted at 3 geographically distant sites. Although it is difficult to isolate the specific cause of yield increase from a series of drainage events, their results suggest that water management practices with mild to severe drainage intensity can enhance rice yields under chronically reductive soil conditions, such as those found in triple cropping systems in the Mekong Delta. This is consistent with observations that positive effects on rice yield have been more frequently reported in wet paddy fields (i.e., fields with consistently low drainability) than in dry paddy fields in Japan. Such conditions may reduce rice yield by promoting the accumulation of toxic substances that inhibit root growth. Therefore, mitigating chronically reductive soil conditions should be prioritized in affected areas (schedule A in Fig. 1). Soil water status during fallow periods and management of organic matter, especially harvested rice straw, are also drivers of soil redox conditions in rice-growing season (Fig. 2). In contrast, under non-chronically reductive soil conditions—such as dry fields and paddy-upland rotation fields—well-planned water management practices that account for crop growth stage (schedule B in Fig. 1) are necessary to achieve optimum yield. For example, Norton et al. (2017) reported that safe AWD

Fig. 2 Environmental and agronomic factors influencing the degree of soil reduction and the corresponding requirements for improving rice yield through water management practices



applied until the flowering stage significantly increased rice yield by 9.0–9.8% compared to CF in a two-year dry-season field experiment in Bangladesh. Similarly, Hoang et al. (2023) reported a 4.4% yield increase with AWD relative to CF under a double rice cropping system in central Vietnam.

Consequently, the schedule of water management practices for improved rice yield aligns with rice physiological stages (Fig. 1) and should be optimized and localized according to environmental and agronomic settings (Fig. 2). When implementing AWD or MiDi, there is limited potential to extend drainage duration, but room remains to adjust drainage intensity for yield enhancement. Through such optimization and localization, water management practices have the potential to serve as a climate-smart agricultural strategy that delivers triple benefits: improved water use efficiency, reduced GHG emissions, and increased rice yield. Beyond the capabilities of water management alone, integrated approaches—such as combining these practices with organic amendments, improved rice varieties, and/or biochar application (Qian et al. 2023; Lou et al. 2024)—should be explored in future research with careful attention to synergies and trade-offs involving soil redox dynamics, GHG emissions, and the uptake of heavy metals by rice. Finally, it should be noted that the optimum drainage intensity differs between CH₄ emission reduction and rice yield improvement. The latter generally requires milder drainage, while the optimum level for farm management under carbon credit schemes may vary depending on credit pricing.

Conclusion

This study synthesized the findings of 11 meta-analyses to assess the impacts of water management practices on GHG emissions and rice yield in paddy fields. The aggregated results confirmed that practices, such as AWD and MiDi, significantly reduce CH₄ emissions and water use, while increasing N₂O emissions. Although yield responses varied, mild-intensity drainage schemes, such as safe AWD, generally avoided yield penalties and, in some cases, enhanced productivity. For water management to function effectively as a climate-smart agricultural practice, drainage schedules must be optimized according to rice physiological stages and local environmental conditions. Particularly, avoiding water stress during sensitive stages like heading, and mitigating chronic reductive soil conditions are key to ensuring stable or improved yields. With proper design and localization, water management has the potential to offer triple benefits: GHG mitigation, improved water efficiency, and yield enhancement. These co-benefits provide a compelling incentive for adoption by farmers and policymakers alike. Future research should explore integrated approaches that combine water management with organic amendments,

improved varieties, and soil quality-enhancing technologies to further maximize climate and agronomic outcomes.

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