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Mitigation Potential of Greenhouse Gas Emissions Through Nitrogen-Water Management Optimization in Major Asian Rice Regions

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Key Points:

- Synergistic water-nitrogen management increases rice yields 47% and reduces emission intensity 36%, overcoming single-practice limitations
- Soil pH, fertilizer type and precipitation are key factors determining the effectiveness of combined rice management practices
- Alternate Wetting and Drying is suitable across 67% of major Asian rice regions, enabling combined optimization to reduce nitrogen inputs by 31% and GHGI by 49%

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Rice production represents a major global food source and a significant contributor to greenhouse gas (GHG) emissions. While nitrogen fertilization and water-saving irrigation are recognized as effective GHG mitigation strategies in rice cultivation, their synergistic effects and underlying mechanisms remain inadequately characterized. Based on 2,689 observations from 203 peer-reviewed articles across 129 sites in major Asian rice cultivation areas, this meta-analysis quantifies the comprehensive impacts of coupled water-nitrogen management on rice yield and GHG emissions. Results revealed that nitrogen fertilization alone increased yield by 38.26% but elevated global warming potential (GWP) by 56.98%, whereas Alternate Wetting and Drying (AWD) irrigation reduced CH_4 emissions (50.71%) and GWP (43.73%) without significantly affecting yield. Combined implementation of both practices increased yield by 46.67% while reducing yield-scaled GWP (GHGI) by 36.17%. Under AWD conditions, nitrogen application rates of 180–270 kg ha^{-1} maximized GHGI reduction potential (42.31%). Random forest analysis identified soil pH, fertilizer type and precipitation as key determinants of mitigation efficacy. Our spatially-explicit water-nitrogen optimization model demonstrated that 67% of regional rice fields are suitable for AWD implementation, and that current nitrogen inputs could be reduced by 31% while maintaining yields and achieving a 49% reduction in GHGI. This study reveals critical water-nitrogen synergistic mechanisms in rice agroecosystems and provides quantitative frameworks for optimizing management practices at regional scales, offering a sustainable pathway toward achieving future food security and climate change mitigation goals in Earth's most productive rice regions.

Plain Language Summary Rice feeds over half the world's population but produces greenhouse gases that contribute to climate change. Major Asian rice regions, contributing 86% of global production, face multiple challenges including water scarcity, food security, and greenhouse gas (GHG) emissions. Although certain water and nitrogen management practices have demonstrated potential for reducing GHG emissions, their synergistic effects have not been systematically quantified, and optimized implementation strategies for practical guidance remain lacking. Through a comprehensive synthesis of existing literature, we discovered that integrating AWD (a water-saving irrigation technique) with optimized nitrogen fertilization significantly enhances crop yields while reducing GHG emissions. Our spatially explicit water-nitrogen optimization model revealed that over two-thirds of rice cultivation areas in the region are suitable for AWD implementation. The concurrent optimization of water and nitrogen management delivers multiple benefits: conservation of critical water and fertilizer resources alongside a remarkable 49% reduction in GHG emission intensity, all while maintaining productivity levels. These findings provide a viable pathway for Asian rice production systems to simultaneously achieve food security and environmental protection objectives, with significant implications for global sustainable agricultural development.

1. Introduction

Rice (*Oryza sativa* L.) constitutes a critical global food source that supports over half of the world's population (Yuan et al., 2021). Currently, global rice cultivation covers approximately 170 million hectares, representing 11% of global cropland, with annual production exceeding 500 million tons (Y. Liu et al., 2021; X. Wang et al., 2023), playing a crucial role in ensuring food security. Concurrently, rice agroecosystems represent significant sources of agricultural greenhouse gas (GHG) emissions, contributing approximately 22% of global

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agricultural CH_4 emissions and 11% of N_2O emissions (IPCC, 2022; Qian et al., 2023; Q. Wang et al., 2020), ranking among the most GHG-intensive cereal crop systems globally. Rice cultivation in tropical and subtropical Asia represents 77% of global rice area and contributes 86% of global rice production (FAO, 2025; Muthayya et al., 2014; Yuan et al., 2022). This region exhibits distinctive monsoon climate characteristics and faces multiple challenges including water scarcity, food security pressures, and nitrogen overuse, making it a critical region for addressing integrated water-food-environment challenges in global rice systems (Cai et al., 2023; Coggins et al., 2025; Welch et al., 2010). This pressure intensifies as research forecasts indicate rice yields need to increase by 50% by 2050 to meet growing global population demands, necessitating both enhanced production capacity and reduced environmental footprint (Abbass et al., 2022; Ivanovich et al., 2023; Rezaei et al., 2023).

Management practices significantly influence both rice productivity and GHG emissions in paddy systems. While various approaches including variety optimization, cultivation improvement, soil amendment, and straw incorporation demonstrate potential for enhancing yields and reducing GHG emissions (X. Chen et al., 2021; Jiang et al., 2019; B. Li et al., 2024; Liao et al., 2024; Zhao et al., 2016), water and nitrogen management represent the key factors regulating rice productivity and environmental impacts. Water management directly regulates soil redox conditions, thereby influencing CH_4 and N_2O production and emission pathways (Tao et al., 2024); nitrogen not only determines yield potential but also affects GHG dynamics through plant-soil-microbe interactions (Farooq et al., 2022). Moreover, water and nitrogen exhibit complex synergistic effects on rice yield and GHG emissions, with water management influencing nitrogen transformation processes and nitrogen availability affecting plant water use efficiency (Han et al., 2021; Srikanth et al., 2023). Consequently, integrated optimization of irrigation regimes and nitrogen inputs is critical for maximizing rice productivity while minimizing environmental footprints, representing a promising pathway toward sustainable rice production systems (X. Chen et al., 2021; S. M. M. Islam et al., 2022; Nie et al., 2023).

However, previous research on rice water-nitrogen management has predominantly evaluated these factors in isolation, revealing significant limitations in achieving optimal outcomes. Water-saving technologies including Alternate Wetting and Drying (AWD) (Lampayan et al., 2015), Humid Irrigation (HI) (T. T. Liu et al., 2020), and Controlled Irrigation (CI) (Dong et al., 2020) significantly reduce CH_4 emissions by enhancing soil aeration (Hoang et al., 2023; Oo et al., 2018; Runkle et al., 2019), while optimized nitrogen application enhances yields but may increase N_2O emissions (Kim et al., 2016; Z. Yao et al., 2012). Recent meta-analyses reveal variable and sometimes contradictory effects of individual management practices. AWD shows inconsistent yield impacts (from −5.4% to +1.52%) but consistently reduces CH_4 emissions (~50%) while increasing N_2O emissions (Carrijo et al., 2017; Gao et al., 2024; B. Li et al., 2024). These variable outcomes highlight the context-dependency of single-factor approaches and their effectiveness across different environmental conditions. These studies collectively demonstrate that while individual water or nitrogen management practices can achieve certain benefits, they face inherent trade-offs and limitations. Water-saving irrigation may reduce CH_4 emissions but can potentially compromise yields under certain conditions, while optimized nitrogen application enhances productivity but may increase overall GWP (Li et al., 2025). More critically, these single-factor approaches fail to capture the complex biogeochemical interactions between water and nitrogen cycles in rice systems. The interdependence of these factors suggests that their isolated optimization may miss synergistic opportunities for simultaneously enhancing productivity and reducing environmental impacts (Coggins et al., 2025; Mir et al., 2025).

Existing evidence suggests that isolated water or nitrogen management approaches have inherent limitations in balancing productivity enhancement and GHG mitigation objectives, thereby establishing integrated water-nitrogen management as a critical area for scientific advancement (Ren et al., 2025). Despite growing interest in integrated approaches, several critical knowledge gaps persist: First, synergistic effects of water-nitrogen coupling have not been systematically quantified, particularly regarding how environmental factors modulate these effects across varied nitrogen inputs and irrigation regimes (K. Liang et al., 2016; Sudhir-Yadav et al., 2014); Second, environmental factors mediating water-nitrogen interaction effects and their underlying mechanisms are insufficiently characterized (G. Xu et al., 2018; Q. Zhou et al., 2017), lacking systematic identification of key drivers and quantitative assessment of their relative importance (Sun et al., 2018; Y. Zhang et al., 2023); Third and most critically, spatially explicit frameworks for optimizing water-nitrogen management at regional scales are absent. This absence impedes regional implementation of sustainable rice management strategies. Specifically, the lack of spatially explicit frameworks limits our understanding of AWD-suitable areas across diverse landscapes. It also constrains the development of nitrogen optimization protocols tailored to environmental heterogeneity. Furthermore, quantitative assessment of GHG mitigation potential achievable through water-nitrogen coupled management remains inadequately characterized. The current literature lacks comprehensive regional-scale assessment and optimization frameworks necessary to translate experimental findings into actionable management recommendations for practitioners. Systematic research on water-nitrogen coupled management and optimization is especially urgent in tropical and subtropical Asian rice-growing areas, which constitute the core of global rice production.

In this study, we conducted a comprehensive meta-analysis based on 2,689 observations from 203 peer-reviewed articles across 129 sites in major Asian rice-growing regions to investigate mechanisms underlying water-nitrogen coupled management effects on rice productivity and GHG emissions. Through an integrated framework combining meta-analysis, machine learning and spatial optimization modeling (Figure S4 in Supporting Information S1), we aimed to: (a) quantify effects of different nitrogen application rates and six irrigation methods on rice yields, GHG emissions, and yield-scaled emission intensity, and assess synergistic benefits of nitrogen-AWD coupled management for concurrent productivity enhancement and emission reduction; (b) identify and explore key environmental factors and management practices that regulate nitrogen-AWD management effectiveness; and (c) conduct regional-scale AWD suitability assessment based on climate, soil, and rice phenology parameters, and optimize nitrogen application rates through random forest modeling to map spatial patterns of GHGI (Greenhouse Gas emission Intensity) reduction potential across the major Asian rice-growing regions.

2. Materials and Methods

2.1. Literature Search and Data Extraction

A comprehensive literature search was conducted using Web of Science (http://apps.webofknowledge.com/) and CNKI (http://www.cnki.net/) through 1 May 2024, using systematic keyword combinations related to irrigation management, nitrogen fertilization, rice productivity, and GHG emissions. Complete search strategies and keyword combinations are detailed in Table S3 in Supporting Information S1. To minimize selection bias, we established rigorous inclusion criteria: (a) field experiments with a minimum of three replicates; (b) experiments encompassing at least one complete crop growth cycle (from planting to harvest); (c) studies incorporating both control and treatment groups, with controls defined as conventional flooding or zero nitrogen application, and treatments involving water-saving irrigation techniques or varied nitrogen application rates; (d) reporting of at least one primary outcome variable (GHG emissions or crop yield); and (e) research conducted within the tropical and subtropical Asian rice-growing region (11.0°S–37.1°N, 60.9°E–141.0°E).

Required data (yield, GHG emissions, and other variables) were extracted directly from tables in the articles. For results presented as statistical graphs (line charts and bar charts), GetData Graph Digitizer software (version 2.20; GetData; http://getdata-graph-digitizer.com/download.php) was employed (X. Yao et al., 2024). In total, 2,689 observational data points from 129 locations across 203 scientific papers met our inclusion criteria (Figure 1). Data from the same publication representing different years or treatment methods were treated as independent observations, as these encompassed distinct management approaches and environmental conditions. This approach enhanced the statistical power of the meta-analysis by increasing the number of independent observations and reducing effect size variance (J. Li et al., 2023).

The comprehensive database incorporated additional parameters including field management practices, initial soil properties, geographical coordinates, climate variables, and experimental year, enabling robust analysis of relationships between water-nitrogen management practices and their effects on yield and GHG emissions (X. Zhang et al., 2020). To facilitate cross-study comparisons, we categorized the extracted data according to standardized classification schemes (L. Li et al., 2024; Z. Yao et al., 2024). Mean annual temperature was stratified into three ranges: ≤10°C, 10–20°C, and ≥20°C; mean annual precipitation (MAP) was classified as ≤500 mm, 500–1,000 mm, and ≥1,000 mm. Soil physicochemical properties were categorized as follows: soil organic carbon (SOC) into ≤10, 10–15, or ≥15 g kg^{-1}; soil total nitrogen (TN) into ≤1.0, 1.0–1.5, or ≥1.5 g kg^{-1}; and soil pH into ≤6.5, 6.5–7.3, and ≥7.3. Nitrogen application rates were divided into five levels: ≤90, 90–180, 180–270, 270–360, and ≥360 kg ha^{-1}.

Based on field water management protocols during rice growth stages (Table S2 in Supporting Information S1), we classified irrigation regimes into six categories: Alternate Wetting and Drying irrigation (AWD), "Shallow-Wet-Dry" irrigation (SWI), Humid Irrigation (HI), Controlled Irrigation (CI), Dry Cultivation (DC), and Rainfed Irrigation. When explicitly stated, AWD was further differentiated into mild alternate wetting and drying

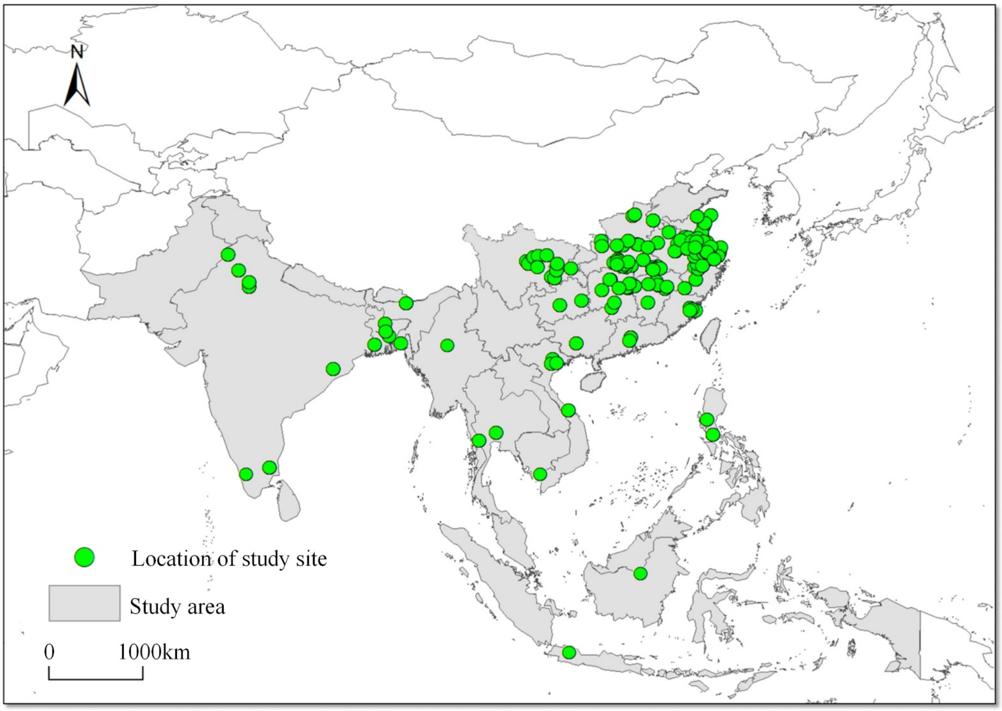

Figure 1. Locations of experimental sites included in this study.

irrigation and severe alternate wetting and drying irrigation. Detailed descriptions of water management practices and their classification criteria are provided in Table S1 in Supporting Information S1. To comprehensively evaluate potential mitigation strategies for yield-scaled global warming potential (GWP) emissions, we analyzed additional management practices including straw incorporation, reduced tillage, fertilization frequency and timing optimization, and alternative cropping systems, assessing their effectiveness in reducing GHG emissions while maintaining or enhancing rice yields.

We extracted GWP and GHGI values directly from articles when reported. For studies reporting only CH_4 and N_2O emissions with rice yield, we calculated GWP as CO_2 equivalent (100-year time horizon) using IPCC (2022) formulas:

$$GWP = 27 \times CH_4 + 273 \times N_2O \tag{1}$$

$$GHGI = GWP/Y \tag{2}$$

where GWP represents GWP (kg CO_2-eq ha^{-1}), N_2O and CH_4 represent nitrous oxide and methane emissions respectively, GHGI denotes yield-scaled GHG emission intensity (kg CO_2-eq kg^{-1}), and Y represents rice yield (kg ha^{-1}).

2.2. Meta-Analysis

Effect size quantifies the magnitude of treatment effects relative to control conditions. In this study, we employed the log response ratio (ln R) as the effect size metric to evaluate rice yield and GHG emission responses to field water and nitrogen management interventions (Hedges et al., 1999). The response ratio was calculated as:

$$\ln R = \ln\left(\frac{X_t}{X_c}\right) = \ln X_t - \ln X_c \tag{3}$$

where R is the response ratio, X_t and X_c denote the mean values (crop yield or GHG emissions) in treatment and control groups, respectively. ln R represents the effect size (dimensionless). A positive ln R value indicates that the treatment enhanced the response variable relative to control conditions. For each study, within-case variance was calculated as:

$$v = \frac{SD_t^2}{N_t X_t^2} + \frac{SD_c^2}{N_c X_c^2} \tag{4}$$

where v denotes within-case variance, N_t and N_c represent the number of replications in treatment and control groups, respectively, and S_t and S_c are the standard deviations of response variables in treatment and control groups, respectively. When standard deviations were reported in original publications, these values were used directly. For studies lacking standard deviation data, we contacted corresponding authors to request this information; when unavailable, we estimated standard deviation as one-tenth of the mean value, a method commonly employed in ecological meta-analyses and shown to produce reliable results when actual variance data are unavailable (C. Li et al., 2022, S. Li et al., 2022; Luo et al., 2006; Gao et al., 2024).

Given the heterogeneity in regional climate, hydrology, and soil conditions affecting rice yield and GHG emissions, we implemented a random effects model for meta-analysis. This approach integrates effect sizes across diverse studies while accounting for both within-study sampling variance and between-study heterogeneity. The weighted mean effect size ($\ln R_{++}$), individual weights ($S_{\ln R++}$), and 95% confidence intervals (CI) were calculated using:

$$\ln R_{++} = \frac{\sum(\ln R_i \times w_i)}{\sum w_i}, w_i = \frac{1}{v} \tag{5}$$

$$S_{\ln R_{++}} = \frac{1}{\sqrt{\sum w_i}} \tag{6}$$

$$95\%\ \text{CI} = \ln R_{++} \pm 1.96 \times S_{\ln R_{++}} \tag{7}$$

where $\ln R_{++}$ represents the weighted mean effect size, $\ln R_i$ and w_i denote the effect size and weight of the ith observation, respectively, with weights calculated as the reciprocal of within-case variance (v). $S_{\ln R++}$ is the standard deviation of the weighted mean effect size ($\ln R_{++}$). To evaluate effect size significance, we calculated 95% confidence intervals using restricted maximum likelihood parameter estimation. An effect size was considered statistically significant ($P < 0.05$) when its 95% CI did not overlap with zero, with positive and negative intervals indicating significant enhancement or reduction effects, respectively.

To facilitate interpretation, $\ln R_{++}$ was converted to relative change (RC) in percentage (%), using:

$$\text{RC} = \left(e^{\ln R_{++}} - 1\right) \times 100\% \tag{8}$$

The corresponding 95% CI for RC was computed by applying this transformation to the confidence limits of $\ln R_{++}$. RC expresses the difference between treatment and control outcomes as a percentage of the control value, providing an intuitive measure of treatment effects. We assessed publication bias using Egger's regression test and Begg's rank correlation test, with $p < 0.05$ indicating significant bias (Begg & Mazumdar, 1994; Egger et al., 1997). When bias was detected, fail-safe N was calculated to evaluate result robustness, with values $>5k + 10$ (k = number of studies) indicating stable findings unlikely to be affected by unpublished studies (Rosenthal, 1979). Publication bias testing showed no significant bias in most analyses, with fail-safe N tests confirming robust results for the few analyses where bias was detected (see Table S4 in Supporting Information S1).

2.3. Water-Nitrogen Optimization and Emission Reduction Potential Assessment

2.3.1. AWD Suitability Assessment

We assessed AWD suitability following Nelson et al. (2015), which determines spatial suitability based on rice phenology, soil properties, precipitation patterns, and evapotranspiration dynamics (Bo et al., 2022; Nelson et al., 2015; Sander et al., 2017). This approach employs a water balance equation integrating precipitation, evapotranspiration, and percolation rates. Potential evapotranspiration (PET) was calculated using the Penman-Monteith equation (Allen et al., 2006), while potential percolation (Poc) rates were determined based on soil texture classifications (Table S6 in Supporting Information S1). Locations where precipitation is insufficient to offset combined evapotranspiration and percolation are classified as having water deficit conditions—indicating potential suitability for AWD implementation. The proportion of water-deficit days during the growing season determines the overall AWD suitability for each grid cell:

$$P > \text{PET} + \text{Poc: water surplus} \tag{9}$$

$$P \leq \text{PET} + \text{Poc: water deficit (AWD suitable)} \tag{10}$$

where P represents mean daily precipitation (mm d^{-1}), PET is daily PET (mm d^{-1}), and Poc is daily potential percolation (mm d^{-1}). The AWD suitability index (P_{AWD}) is calculated as:

$$P_{\text{AWD}} = \frac{T_{\text{AWD}}}{T} \times 100\% \tag{11}$$

where T_{AWD} is the number of water-deficit days and T is the total growing season duration (days).

Based on previous research demonstrating topographical constraints on AWD implementation (Bouman et al., 2007; L. Feng et al., 2007), areas with slopes ≥6° were deemed unsuitable. Sites with $P_{\text{AWD}} \geq 50\%$ and slopes <6° were classified as AWD-suitable and included in subsequent GHGI mitigation analysis.

2.3.2. GHGI Reduction Potential Assessment

Conventional approaches to quantifying GHGI mitigation potential typically follow IPCC methodologies, which rely on standardized emission factors and activity data for specific rice production systems. In contrast, we developed a data-driven framework using meta-analysis outcomes and machine learning to predict GHGI reduction potential under varying environmental conditions and management interventions. Our analytical framework evaluated multiple scenarios through separate random forest models: GHGI mitigation under nitrogen optimization (ΔGHGI_N), GHGI mitigation under irrigation optimization (ΔGHGI_AWD), GHGI mitigation under combined nitrogen-irrigation optimization (ΔGHGI_N-AWD), and yield changes under integrated management (ΔYield_N-AWD). For each scenario, GHGI mitigation potential was quantified by integrating regional biophysical variables with management parameters through predictive modeling.

We implemented a random forest algorithm(Breiman, 2001) with nitrogen application rate (n), irrigation regime (w), and key environmental factors (X) as predictors, and GHGI reduction potential (ΔGHGI) as the response variable. The model structure can be expressed as:

$$\Delta\text{GWGI} = f(n, w, X) \tag{12}$$

where ΔGHGI represents the percentage reduction in GHGI relative to baseline practices, and X encompasses critical environmental variables including Mean annual temperature, MAP, SOC, TN, and soil pH. The data set was partitioned into training (80%) and validation (20%) subsets, with hyperparameters optimized separately for each response variable by minimizing out-of-bag (OOB) root mean square error (RMSE). Detailed optimization parameters for each model are provided in Table S5 in Supporting Information S1. Model performance was evaluated using five-fold cross-validation, with R^2 and RMSE as evaluation metrics (Figure S3 in Supporting Information S1).

For optimization purposes, irrigation regimes were classified as either AWD (w_{AWD}) or conventional irrigation (w_{CI}) based on the aforementioned suitability analysis. Nitrogen rate optimization employed a grid search algorithm with 10 kg ha^{-1} increments, identifying the application rate that maximized GHGI reduction while maintaining baseline yields. Baseline yields were defined as average yield under current management practices, with the constraint that optimized management must maintain at least 100% of baseline productivity. The feasible nitrogen application range was set at 50–500 kg N ha^{-1}, encompassing the spectrum from minimal fertilization (below typical agronomic recommendations) to excessive application rates (above agronomic optima), consistent

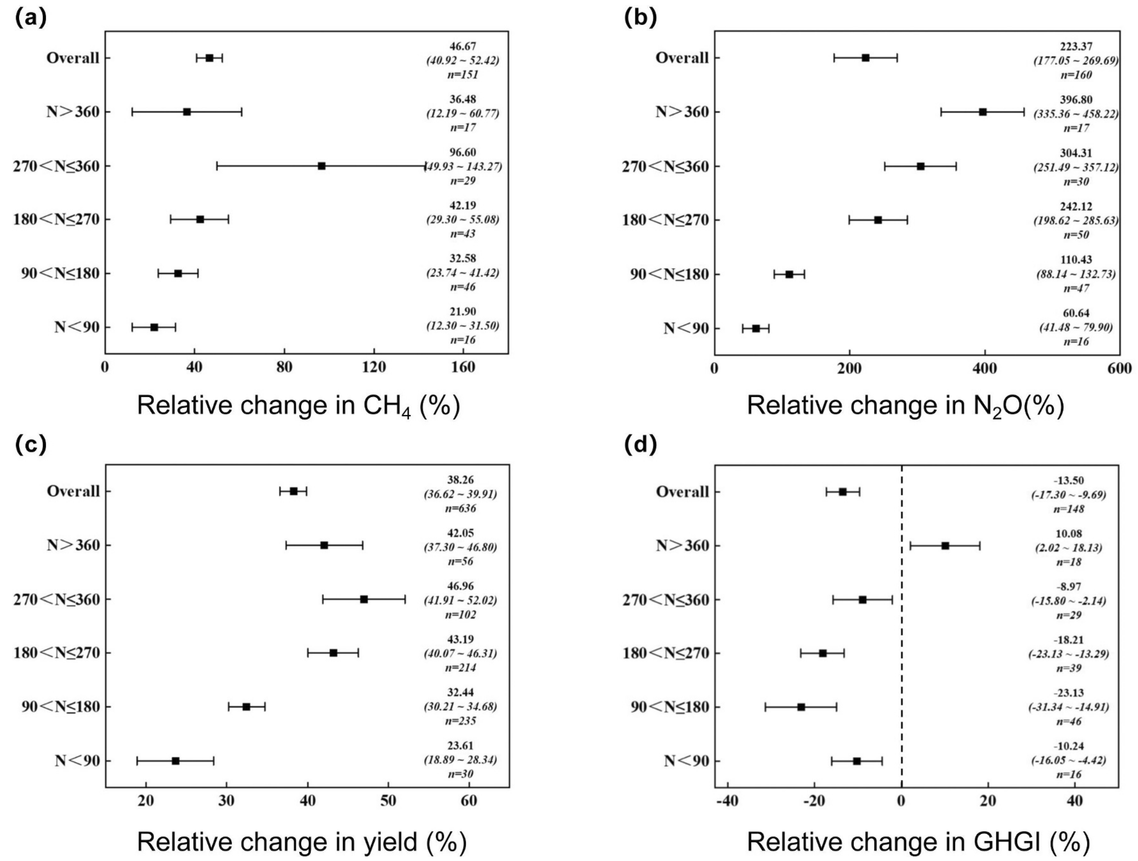

Figure 2. Responses of rice yield and greenhouse gas emissions to nitrogen fertilization. (a) CH_4 emissions, (b) N_2O emissions, (c) grain yield, and (d) yield-scaled global warming potential (GHGI). Data are presented as mean effect sizes with 95% confidence intervals and "*n*" indicate sample sizes.

with the nitrogen application ranges commonly reported in the literature (H. Liang et al., 2021; Y. Liu et al., 2024). The optimization objective function was defined as:

$$s_{\mathrm{opt}} = \max \Delta \mathrm{GWGI}(n, w, X), s.t. R_{\mathrm{yield}} \geq 1, n_{\min} \leq n \leq n_{\max}, w \in \{0, 1\} \tag{13}$$

where R_{yield} represents the yield prediction model, $R_{\mathrm{yield}} \geq 1$ represents that yield must at least reach the baseline yield threshold, and $n_{\min}$ and $n_{\max}$ define the feasible range of nitrogen application rates.

3. Results

3.1. Nitrogen Fertilization Effects on Yield and GHG Emissions

Nitrogen fertilization effects on rice yield and GHG emissions were quantified across different application rates and environmental conditions. Our meta-analysis demonstrated complex trade-offs between productivity gains and environmental impacts. Specifically, our analysis revealed that relative to unfertilized controls (Figure 2), nitrogen application increased CH_4 emissions by 46.67% (95% CI: 40.92%–52.42%), N_2O emissions by 223% (95% CI: 177.05%–269.69%), resulting in a 56.98% increase in GWP. However, due to substantial yield enhancement (38.26%, 95% CI: 36.62%–39.91%), the yield-scaled GWP (GHGI) decreased by −13.50% (95% CI: −17.30% to −9.69%), indicating that nitrogen fertilization improved GHG efficiency per unit of rice produced.

Nitrogen fertilization effects exhibited clear dose-response relationships. Yield enhancement progressively strengthened with increasing nitrogen application rates, peaking at 46.96% with applications of 270–360 kg N ha^{-1}, then declining at rates exceeding 360 kg N ha^{-1}. The lowest yield response (23.61%) occurred at rates below 90 kg N ha^{-1}. CH_4 emissions followed similar patterns, with maximum increases (96.59%) at 270–360 kg N ha^{-1} and minimal increases (21.90%) at rates below 90 kg N ha^{-1}. GHGI exhibited a contrasting pattern: applications

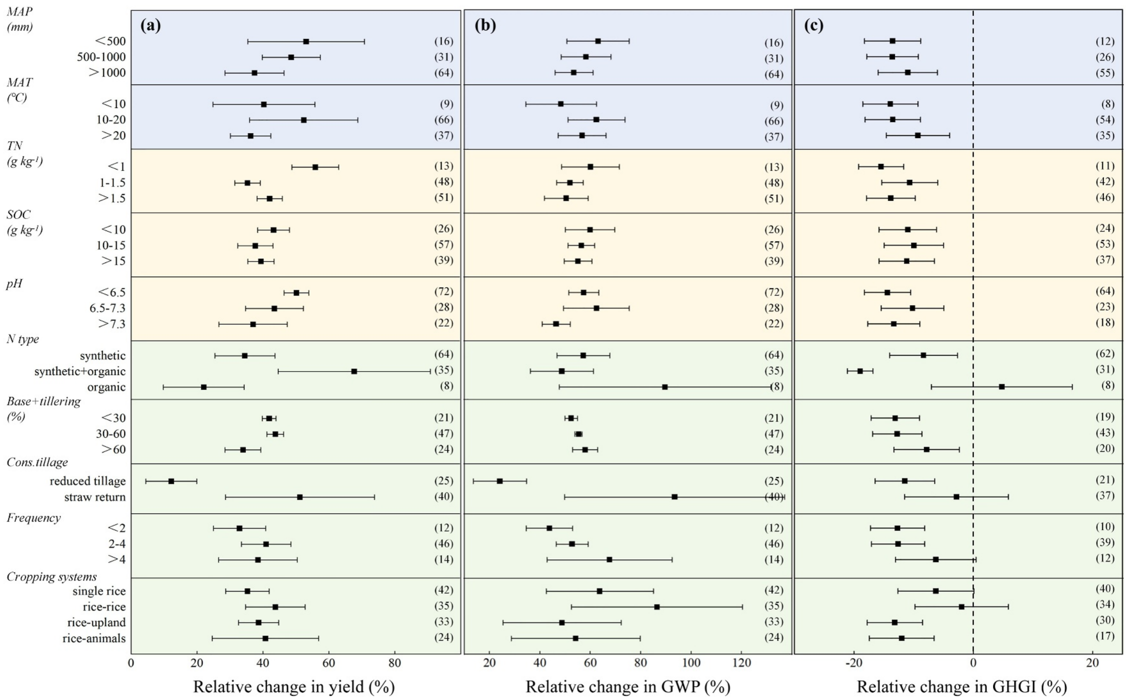

Figure 3. Environmental regulation of nitrogen fertilization effects. (a) yield, (b) global warming potential (GWP), and (c) yield-scaled GWP under varying soil, climate and management conditions. The numbers of observations included were indicated in parentheses.

exceeding 360 kg N ha^{-1} increased GHGI by 10.08%, while lower rates reduced GHGI to varying degrees. The optimal reduction (−23.12%) occurred at 90–180 kg N ha^{-1}, followed by 180–270 kg N ha^{-1} (−18.21%), with rates below 90 and between 270 and 360 kg N ha^{-1} reducing GHGI by 10.24% and 8.97%, respectively.

Soil properties significantly modulated the effects of nitrogen fertilization (Figure 3). In acidic (pH ≤ 6.5) and less fertile soils (SOC ≤ 15 g kg^{-1}, TN ≤ 1.5 g kg^{-1}), nitrogen application resulted in marginal GHG emission increases but substantially larger yield gains, thereby reducing GHGI. Maximum yield responses (50.17%) occurred in acidic soils (pH ≤ 6.5), which also exhibited substantial GHGI reductions (−14.40%). By contrast, near-neutral (6.5 < pH ≤ 7.3) and alkaline (pH > 7.3) soils showed more modest yield increases (43.49% and 36.99%, respectively). Soil nutrient status further influenced nitrogen effects, with nitrogen-depleted soils (TN ≤ 1.0 g kg^{-1}) exhibiting the highest yield response (55.90%) and greatest GHGI reduction (−15.46%). As SOC increased, GHGI reduction initially diminished then intensified, reaching maximum efficiency (−11.61%) at SOC > 15 g kg^{-1}.

Climatic factors also influenced nitrogen fertilization outcomes. As MAP increased, yield response to nitrogen progressively declined, with maximum effectiveness (53.10%) at MAP ≤ 500 mm. GHGI reduction followed a parabolic pattern, peaking (−13.56%) at moderate precipitation levels (500 < MAP ≤ 1,000 mm). Regarding temperature effects, nitrogen-induced yield increases were most pronounced (52.37%) in temperate conditions (10 < MAT ≤ 20°C), while GHGI reductions were greatest (−13.92%) in cooler regions (MAT ≤ 10°C).

Management practices significantly modified nitrogen effects. Combined synthetic-organic fertilization and straw incorporation enhanced yield responses compared to unfertilized controls. Conversely, organic-only fertilization, reduced tillage, infrequent application (≤2 applications), and higher basal + tillering fertilizer ratios (>60%) resulted in more modest yield improvements. Maximum GHGI reductions occurred with organic-only fertilization, low basal + tillering fertilizer ratios (<30%), and rice-upland rotations. Organic-only fertilization, straw incorporation, and rice-upland rotations produced smaller GHGI reductions.

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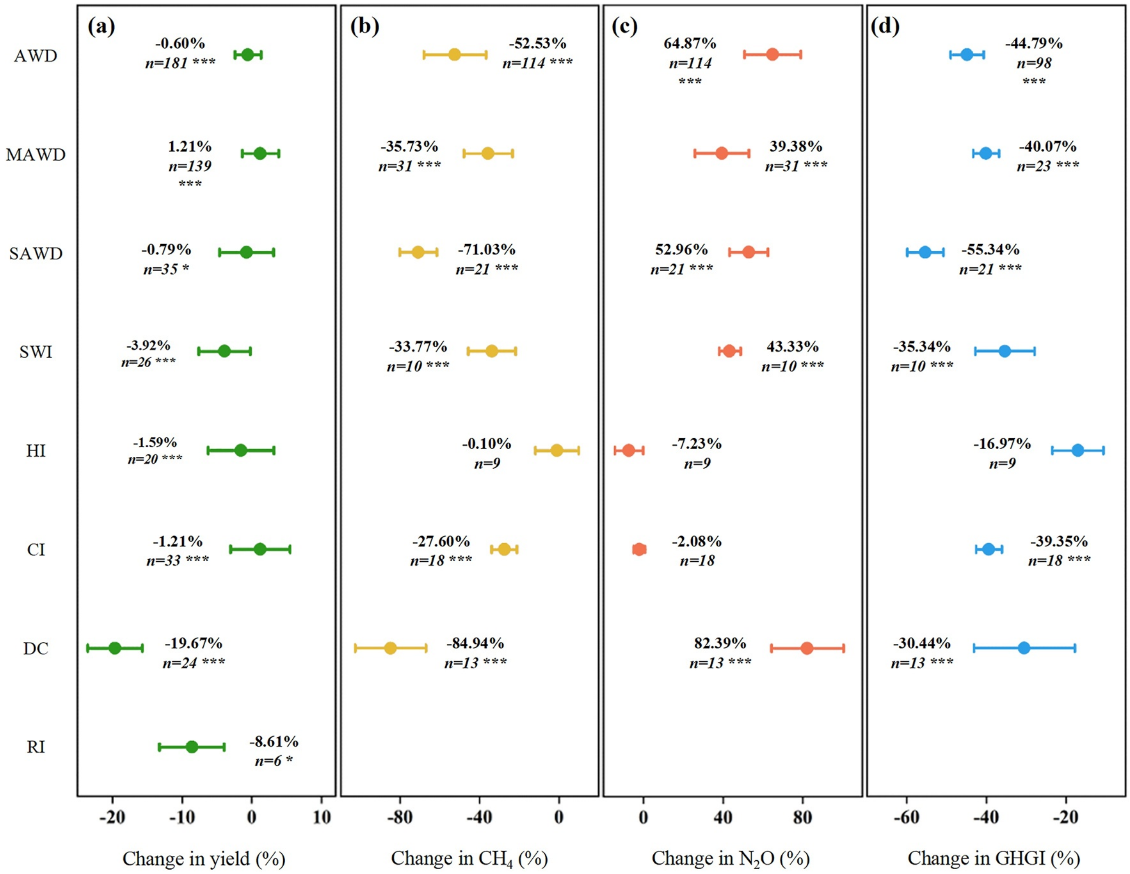

Figure 4. Impact of water management strategies on rice production and greenhouse gas emissions. (a) Grain yield, (b) CH_4 emissions, (c) N_2O emissions, and (d) yield-scaled global warming potential. *, ** and *** indicate $P < 0.05$, 0.01 and 0.001, respectively.

3.2. Water Management Effects on Yield and GHG Emissions

The effects of eight water management strategies on rice yield and GHG emissions were evaluated (Figure 4), and we assessed how AWD effectiveness varied across different environmental conditions. Compared to conventional flooding, DC significantly decreased yields by −19.67% (95% CI: −23.59% to −15.75%) but substantially reduced CH_4 emissions by −84.94% (95% CI: −87.20% to −82.67%) despite increasing N_2O emissions by 82.39% (95% CI: 64.21%–100.57%), resulting in net reductions in GWP by −63.54% (95% CI: −72.57% to −54.56%) and GHGI by −30.44% (95% CI: −43.11% to −17.78%). Water-saving technologies including AWD, shallow-wet-dry irrigation (SWI), and controlled irrigation (CI) maintained yields while significantly reducing emissions. These practices reduced CH_4 emissions by an average of 50.74% while increasing N_2O emissions by 53.73%, generating net GWP reductions. Among these techniques, AWD reduced GWP by 43.73%, with mild AWD reducing GWP by 31.61% and severe AWD achieving greater reductions of 60.27%. SWI and CI reduced GWP by 25.62% and 22.43%, respectively. The effect of HI remained indeterminate ($P = 0.779$), possibly due to limited observations. Notably, AWD—the most widely implemented water-saving practice—maintained yields (−0.60%, 95% CI: −1.19%–4.08%) while substantially reducing CH_4 emissions by −52.53% (95% CI: −58.98% to −46.08%), GWP by −43.73% (95% CI: −47.38% to −40.08%), and GHGI by −44.79% (95% CI: −48.93% to −40.65%), These substantial emission reductions while maintaining yields demonstrate AWD's effectiveness as a practical mitigation strategy.

The response of rice yield to AWD varied with environmental conditions, while GHGI reductions remained consistent across contexts (Figure 5). GHGI reductions with AWD varied non-linearly with climate parameters, with maximum reductions observed in high-precipitation regions (MAP ≥ 1,000 mm, −61.16%) and temperate climates (10 ≤ MAT < 20°C, −43.63%). Yield response to AWD shifted from slightly negative (−0.53%) in low-precipitation regions (MAP ≤ 500 mm) to positive (1.08%) in high-precipitation areas (MAP > 1,000 mm).

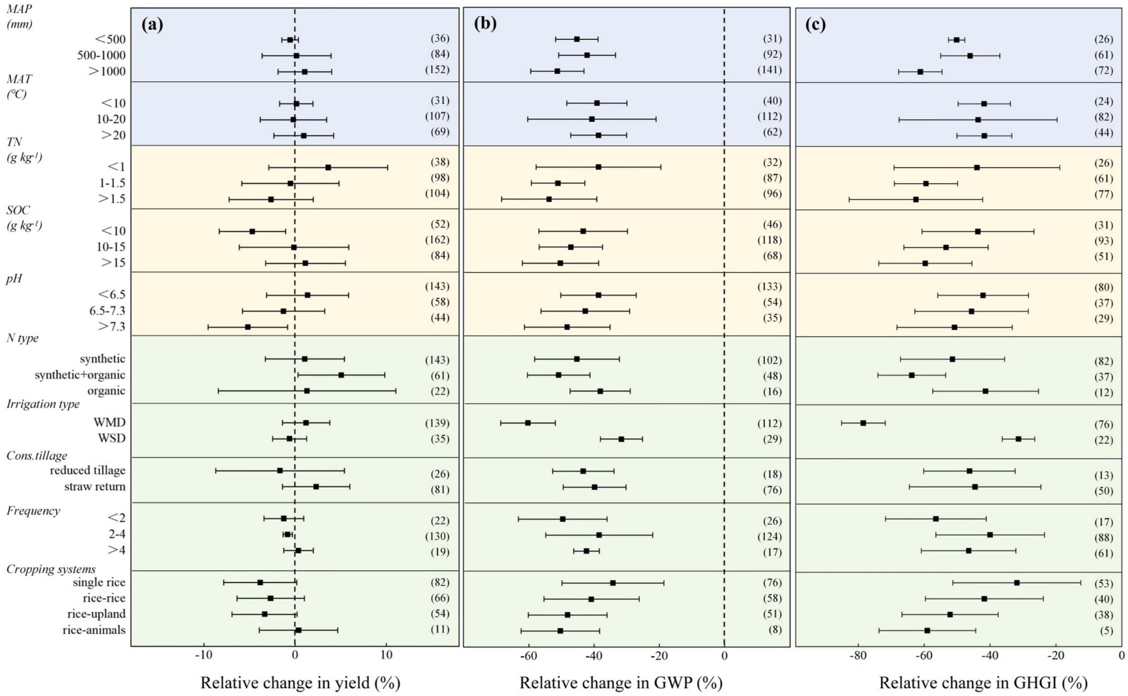

Figure 5. Environmental drivers modulating Alternate Wetting and Drying effectiveness. Changes in (a) grain yield, (b) global warming potential (GWP), and (c) yield-scaled GWP across environmental gradients and management practices. The numbers of observations included were indicated in parentheses.

Similarly, temperature-dependent yield responses followed a U-shaped curve, being slightly positive (+0.14%) in cool regions, negative (−0.18%) in temperate zones, and positive again (0.96%) in warmer areas (MAT ≥ 20°C). However, these yield responses were not statistically significant ($P > 0.05$).This suggests that AWD exhibits strong adaptability across different precipitation conditions, with minimal impact on rice yields regardless of climate variability (Gao et al., 2024). This may be attributed to AWD functioning as a climate-smart agricultural technology that substantially mitigates the impacts of climate variability through proactive water management strategies based on soil water potential thresholds (Ishfaq et al., 2020), supporting its broad applicability for diverse climatic regions.

Soil properties modulated AWD effects, with alkaline soils (pH > 7.3) showing significant yield reductions (−5.18%, 95% CI: −9.54% to −0.82%) but maximum GHGI reductions (−50.78%). GHGI reduction efficacy strengthened with increasing soil fertility, reaching −62.50% and −59.65% at high TN (>1.5 g kg^{-1}) and SOC (>15 g kg^{-1}) levels, respectively.

Management practices further influenced AWD outcomes. When combined with synthetic-organic fertilization, AWD significantly increased yields by 5.08% (95% CI: 0.33%–9.83%), while moderate fertilization frequency (2–4 applications) resulted in minor yield reductions by −0.82% (95% CI: −1.33% o −0.31%). Mild AWD implementation generated higher yields by 1.21% (95% CI: −1.39%–3.81%) than severe AWD. Maximum GHGI reductions occurred with synthetic-organic fertilization (−63.76%), mild AWD (−78.44%), infrequent fertilization (<2 applications, −56.47%), and diversified cropping systems including rice-upland rotation (−52.14%) and rice-animal integration (−59.05%).

3.3. Synergistic Effects of Integrated Nitrogen-AWD Management

We examined the integrated effects of nitrogen fertilization and AWD irrigation on rice productivity and GHGI, and determined the key factors controlling their synergistic interactions (Figure 6; Figure S2 in Supporting Information S1), Compared to controls, integrated management increased rice yields by 46.67% (95% CI: 40.92%–52.42%), substantially exceeding the effects of nitrogen application alone (38.26%) or AWD alone (−0.60%). This 8.4% point additional yield gain demonstrates true synergistic benefits beyond additive effects. The

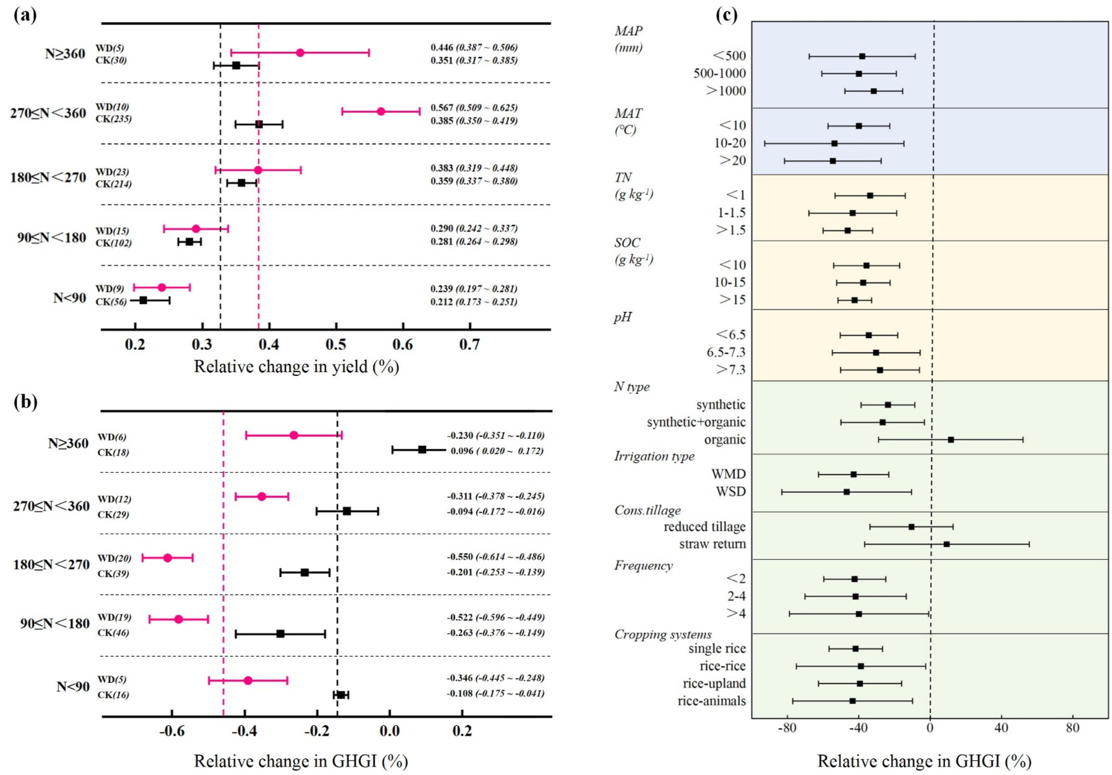

Figure 6. Synergistic effects of nitrogen and Alternate Wetting and Drying management. (a) Grain yield response to combined N-AWD treatment versus *N* alone, (b) GHGI response to combined N-AWD treatment versus *N* alone, and (c) key factors controlling the coupling effects. Red and black dashed lines in (a) and (b) indicate mean effects of combined and single treatments, respectively.

concurrent 36.17% reduction in GHGI (95% CI: −38.98% to −33.36%) indicates that integrated management achieves win-win outcomes for both productivity and emission efficiency.

Concurrent emission reduction benefits were also observed with integrated management. Maximum GHGI reductions (−42.31%) occurred at moderate nitrogen rates (180–270 kg N ha^{-1}), with substantial reductions (−40.67%) also observed at 90–180 kg N ha^{-1}. These findings indicate that moderate nitrogen applications (180–270 kg N ha^{-1}) combined with AWD represent the optimal strategy for simultaneously enhancing yields and reducing emissions.

While integrated nitrogen-AWD management consistently improved both productivity and emissions across diverse environments, effectiveness varied with environmental and management conditions. Relative importance analysis identified soil pH, fertilizer type, MAP, and SOC as the primary factors governing management efficacy (Figure S2 in Supporting Information S1). GHGI reduction effectiveness decreased with increasing soil pH, with maximum reductions (−34.30%) in acidic soils (pH ≤ 6.5), likely due to enhanced nitrogen use efficiency and suppressed methanogenic activity under acidic conditions. Conversely, GHGI reductions strengthened with increasing SOC, reaching 42.31% at SOC > 15 g kg^{-1}. Optimal climatic conditions for integrated management included moderate precipitation (500 < MAP ≤ 1,000 mm, −39.95% GHGI) and high temperatures (MAT > 20°C, −54.62% GHGI). Management practices enhancing synergistic benefits included reduced fertilization frequency (≤2 applications), rice monoculture or rice-animal integration systems, and synthetic-organic fertilization.

3.4. Spatial Assessment of AWD Suitability and GHGI Reduction Potential

Regional-scale spatial analysis was performed to assess AWD suitability and optimize water-nitrogen management for emission reduction potential across major Asian rice regions. Based on integration of precipitation-evapotranspiration dynamics, soil percolation characteristics, and topographical constraints (slope <6°), our spatial analysis revealed that 67% of rice cultivation area across tropical and subtropical Asia met the criteria for

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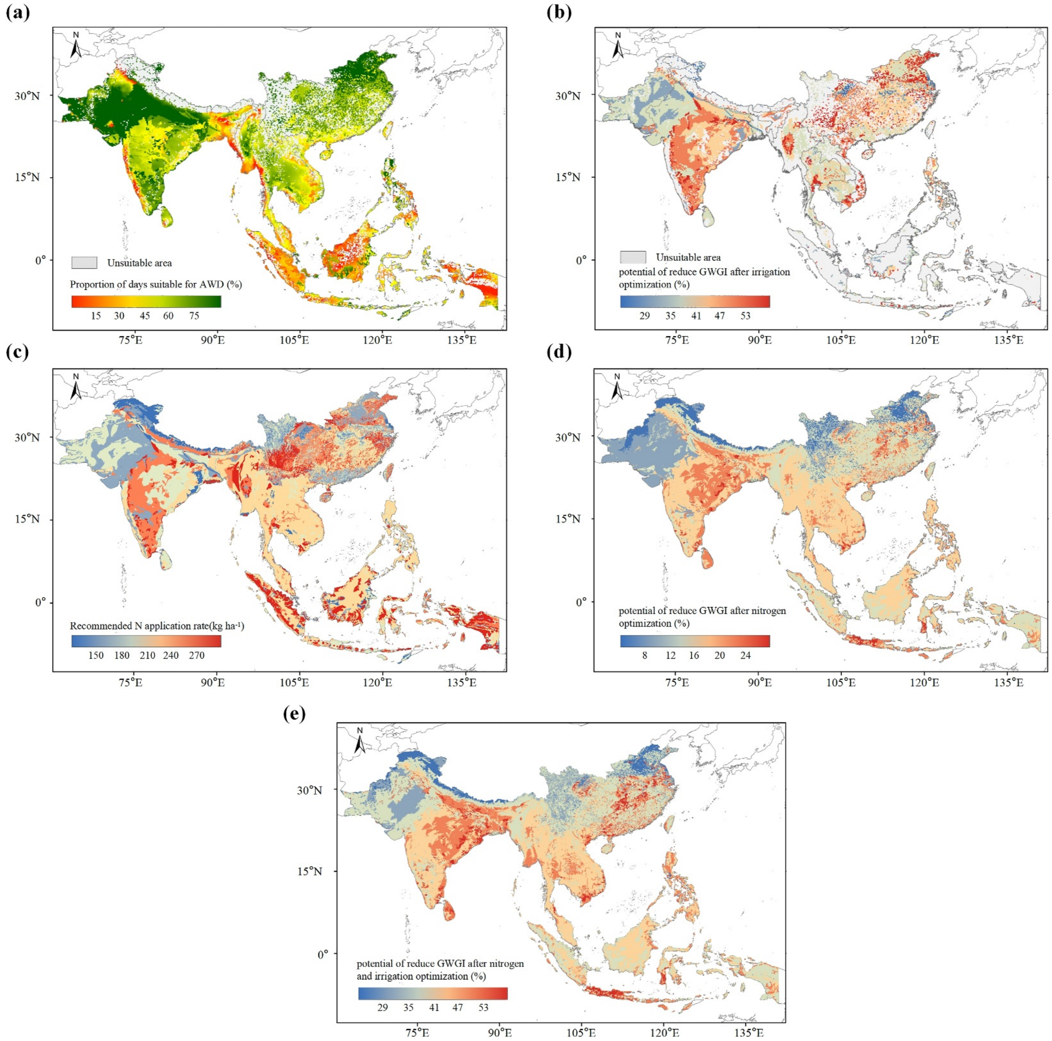

Figure 7. Optimization and benefits of nitrogen application and irrigation. (a) suitability of alternate wetting and drying (AWD), (b) GHGI mitigation potential through AWD, (c) optimized nitrogen application rates, (d) GHGI mitigation potential through optimized nitrogen application, (e) GHGI mitigation potential through optimized nitrogen application and irrigation.

AWD suitability (PAWD ≥ 50%) (Figure 7a). AWD-suitable areas were distributed across southern China, the Indian Peninsula, mainland Southeast Asia (including Myanmar, Thailand, Cambodia, and Vietnam), and specific regions of island Southeast Asia, notably northern Luzon and western Visayas in the Philippines, and Java in Indonesia.

Implementation of AWD across suitable areas, without nitrogen optimization, would reduce regional GHGI by 43% relative to conventional irrigation practices (Figure 7b). The spatial distribution of GHGI reduction varied from 20% to 60%, with highest reduction potentials observed in eastern and central China, southern India, Vietnam, southern Thailand, and central Myanmar.

Random forest modeling under yield maintenance constraints determined that regional nitrogen inputs could be reduced by 23% on average (Figure 7c). This nitrogen optimization alone resulted in an 18% GHGI reduction (Figure 7d). The potential for nitrogen reduction varied across countries, with mean values of 21.7% for India, 20.4% for the Philippines, 19.8% for Indonesia, 18.6% for Myanmar, and 17.4% for China.

Combined optimization of both irrigation (AWD) and nitrogen management (Figure 7e) enabled a 31% reduction in nitrogen inputs while maintaining yields and achieving a 49% decrease in GHGI across AWD-suitable areas.

The spatial distribution of this combined mitigation potential showed considerable heterogeneity throughout the study region.

4. Discussion

4.1. Synergistic Benefits of Integrated Nitrogen and AWD Management

Our meta-analysis demonstrates that integrating nitrogen fertilization with AWD irrigation yields substantial dual benefits: a 46.67% increased rice yields concurrent with a 36.17% reduced GHGI—achieving the elusive win-win of enhanced productivity with diminished climate impact.

4.1.1. Maintaining Rice Yields by *N* and AWD

Nitrogen fertilization and AWD contribute to yield maintenance through distinct but complementary mechanisms. Nitrogen fertilization enhances rice productivity through multiple physiological pathways including improved chlorophyll content, photosynthetic efficiency, and enhanced nutrient cycling (X. Wang et al., 2019; Yoon et al., 2020). However, excessive applications (>360 kg N ha^{-1}) prove counterproductive, reducing yields through nitrate accumulation, increased lodging susceptibility, and heightened pest pressure(Dai et al., 2018; Zeng et al., 2024; Y. Zhang et al., 2022; W. Zhou et al., 2022). AWD maintains yields in rice systems through improved plant stress resilience, enhanced root proliferation, controlled ineffective tillering, and improved soil aeration that promotes root respiration and nutrient acquisition (Chu et al., 2018; Z. Li et al., 2018), While severe AWD can impose water stress, mild AWD maintains or slightly enhances yields (J. Yang et al., 2017; H. Zhang et al., 2010; Z. Li et al., 2018).

The integration of these approaches generates synergistic yield benefits (46.67%) that substantially exceed those of nitrogen application (38.26%) or AWD (−0.60%) implemented separately. The additional yield gain demonstrates true synergistic mechanisms operating through complementary pathways. AWD modifies soil redox conditions to enhance nitrogen cycling between ammonium and nitrate forms, improving nitrogen bioavailability, particularly in acidic soils where our analysis showed maximum effectiveness (Tang et al., 2024; W. Zhang et al., 2021). Simultaneously, AWD optimizes rhizosphere conditions to promote root development and function, enhancing nitrogen uptake efficiency, especially in less fertile soils or with moderate nitrogen rates (L. Liu et al., 2013; P. Xu et al., 2020). The synergy extends beyond additive effects through temporal coordination where appropriate nitrogen inputs compensate for potential minor yield penalties from AWD implementation, while AWD timing optimizes nitrogen availability during critical growth phases (Q. Hu et al., 2023; Su et al., 2023; Vitali, Moretti, et al., 2024, Vitali, Russo, et al., 2024; Q. Xiong et al., 2018). Combined management enhances nutrient accumulation in rice tissues, improves photosynthetic capacity (W. Zhang et al., 2021), upregulates nitrogen metabolism enzymes including nitrate reductase and glutamine/glutamate synthetases (Dai et al., 2018), delays protein degradation, and enhances translocation of nutrients and photosynthates to developing grains during grain-filling (G. Xu et al., 2018; P. Xu et al., 2020).

4.1.2. Reducing Global Warming Potential by *N* and AWD

Nitrogen fertilization and AWD exert contrasting effects on GHG emissions, with their integration achieving net emission reductions. Nitrogen fertilization increases GHG emissions through increased plant biomass providing methanogenic substrates, enhanced CH_4 transport through plant aerenchyma, and stimulated nitrification-denitrification processes elevating N_2O emissions (Bao et al., 2016; He et al., 2017). Conversely, AWD substantially reduces CH_4 emissions through altered soil redox dynamics, where periodic aerobic conditions inhibit anaerobic methanogens while promoting methanotrophic activity (Jain et al., 2004; Shiratori et al., 2007). Although AWD increases N_2O emissions, these contribute substantially less to overall GWP than the corresponding CH_4 reductions, resulting in net GWP decreases.

The combined effect of nitrogen and AWD on GHG emissions reflects their interactive influence on biogeochemical processes that creates emission reduction pathways unavailable to individual practices. Under conventional flooding, nitrogen application maximizes methanogenic activity and plant-mediated CH_4 transport. In contrast, AWD implementation with nitrogen fertilization accelerates microbial turnover, enhances soil carbon sequestration, and reduces rhizosphere priming effects on CH_4 production (Zhu et al., 2018). The integration also optimizes biogeochemical processes where nitrogen-enhanced root development under AWD conditions

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promotes aerenchyma formation and radial oxygen loss (Iqbal et al., 2021; Jiménez & Pedersen, 2023), expanding rhizosphere oxidation zones that favor CH_4 oxidation while creating oxic-anoxic interfaces for complete nitrogen cycling (Ding et al., 2019), thereby enabling coordinated regulation of both methane and nitrous oxide emissions. The integrated approach significantly reduces GHGI, with our results indicating optimal effectiveness at moderate nitrogen rates (<270 kg ha^{-1}). At higher nitrogen applications, the mitigation potential becomes limited, possibly because baseline CH_4 emissions are already constrained under excessive fertilization conditions, reducing the scope for further AWD-mediated emission reductions.

4.2. Drivers Regulating the Variation in Treatment Effects

Our meta-analysis identified multiple environmental and management factors that regulate the efficacy of integrated nitrogen-AWD management for yield enhancement and emission reduction.

Climate parameters significantly influence management outcomes, with nitrogen application and AWD most effectively reducing GHGI under lower precipitation conditions. This finding has particular relevance for monsoon Asia, where uneven precipitation distribution results in prolonged waterlogging during rainy seasons—a key driver of CH_4 emissions. Higher precipitation compromises AWD effectiveness by limiting soil oxygen diffusion and maintaining anaerobic conditions. This aligns with previous research demonstrating that regions or seasons with lower rainfall are more suitable for AWD implementation (Leon & Izumi, 2022; L. Li et al., 2024). Temperature effects were comparatively modest, likely due to limited thermal variation across the study region and the modulating influence of irrigation management on soil temperature regimes.

Soil properties, particularly pH, emerged as the dominant predictor of nitrogen-AWD effectiveness (Figure S2 in Supporting Information S1). This enhanced performance in acidic environments likely stems from multiple mechanisms: nitrogen and AWD synergistically promote root development in acidic soils, while alkaline conditions increase exchangeable sodium that inhibits growth through Na^+ toxicity (Zheng et al., 2023); high pH accelerates ammonia volatilization, reducing nitrogen use efficiency (S. Li et al., 2022; Selvarajh & Ch'ng, 2022).; methanogenic activity peaks in neutral-to-alkaline conditions (Pan et al., 2021), making AWD's CH_4-suppressing effects more pronounced in acidic soils (Jia et al., 2019); and nitrogen fertilization effects on CH_4 emissions diminish with increasing pH (Tang et al., 2024). The relationship between soil pH and N_2O dynamics adds further complexity to management effectiveness. While alkaline soils exhibit enhanced N_2O reductase activity that reduces net N_2O emissions(Kong et al., 2024; C. Wang et al., 2018; Z. Yang et al., 2020), this advantage is offset by reduced nitrogen retention and plant uptake efficiency. In contrast, acidic soils achieve effective N_2O control through enhanced nitrogen use efficiency (Hou et al., 2024; L. Huang et al., 2017, M. Huang et al., 2017). Soil fertility parameters further modulated management outcomes, with integrated management most effectively reducing GHGI in soils with elevated SOC and TN. Carbon-rich soils provide abundant substrates that amplify AWD's aeration effects (Ye et al., 2016), while nitrogen-rich soils show diminished yield response to additional fertilization (M. Huang et al., 2017; Rahman & Parkinson, 2007; C. Wang et al., 2018).

Management practices significantly modified treatment outcomes, with partial organic substitution and optimized basal + tillering fertilization ratios showing particular promise. Different organic amendments variably influence CH_4 emissions (J. Feng et al., 2013; M. Hu et al., 2024). While organic resources are abundant but underutilized in the study region, judicious synthetic-organic combinations can maintain yields while reducing GWP. However, excessive organic substitution (>40%) risks increased CH_4 emissions through enhanced organic matter mineralization (S. Li et al., 2022; X. Zhang et al., 2020). Fertilization timing and distribution strategies proved critical for optimizing synergistic benefits. Optimal results were achieved with basal + tillering proportions ≤60% applied in 2–4 split applications, likely because extended fertilization better matches crop demand throughout development, enhancing biomass accumulation and yield (J. Huang et al., 2022). Cropping system effects on GHGI were less pronounced, potentially because system selection is largely determined by regional climate parameters, particularly temperature and precipitation regimes (J. Li et al., 2024; Vitali, Moretti, et al., 2024, Vitali, Russo, et al., 2024), making it difficult to accurately assess the independent effects of cropping systems.

Complex interactions exist between these driving factors, necessitating integrated assessment approaches for effective implementation (S. Li et al., 2018). For example, soil pH not only directly influences methanogen activity but also modulates AWD mitigation efficacy by regulating nitrogen transformation processes (R. Xiong et al., 2024). Similarly, climate conditions affect organic matter mineralization rates, thereby altering soil responses to water-nitrogen management (L. Zhang et al., 2025). Effective implementation of emission reduction strategies therefore requires comprehensive assessment of multiple factors and development of regionally differentiated approaches based on local environmental and management conditions (Gao et al., 2024). Future research should further elucidate interaction mechanisms between these drivers to inform precision management policies that can optimize synergistic benefits across diverse agroecological contexts (Xing et al., 2025).

4.3. Regional GHGI Reduction Potential and Implementation

Our analysis demonstrates that integrated optimization of irrigation and nitrogen management significantly outperforms single-intervention approaches in balancing productivity and GHG mitigation in major rice-growing regions of Asia. The 49% GHGI reduction achievable through combined water-nitrogen management aligns with previous estimates(46.8%; Bo et al., 2022), while extending beyond prior research by quantifying the additive benefits of concurrent nitrogen optimization with AWD implementation (Table S7 in Supporting Information S1).

The spatial assessment of GHGI mitigation potential through AWD implementation reveals substantial regional heterogeneity, reflecting underlying differences in biophysical conditions and management practices(Carrijo et al., 2017; Gao et al., 2024). Maximum GHGI reductions from AWD adoption are projected for southern China, eastern India, Myanmar's Irrawaddy Basin plains, and Thailand's Chao Phraya plains—areas characterized by favorable combinations of flat topography, suitable precipitation regimes, and fertile soils that our analysis identified as optimal for AWD effectiveness. Similarly substantial reduction potential is evident in specific regions of the Philippines and Indonesia, where high ambient temperatures, extended flooding periods in conventional rice cultivation, and predominance of acidic soils (pH < 6.5) contribute to elevated baseline methane emissions, thereby enhancing the relative mitigation benefits of AWD implementation (S. F. Islam et al., 2018; Kritee et al., 2018).

Regional variation in nitrogen optimization potential correlates strongly with soil properties and management intensity. Major rice-producing areas in central China, Indochina, India, the Philippines, and Indonesia exhibit greater potential for nitrogen reduction without yield penalties. This spatial pattern is consistent with our meta-analysis findings that soils with elevated SOC and TN content show diminished yield response to nitrogen fertilization, thus permitting reduced inputs while maintaining productivity. These regions are concurrently recognized as hotspots of excessive fertilizer application (Z. Cui et al., 2018; Ju et al., 2009; X. Zhang et al., 2015). Despite optimization opportunities, certain areas—particularly in eastern China, Myanmar, and India—require higher nitrogen inputs (>240 kg N ha^{-1}) to sustain yields, likely reflecting the predominance of intensive rice monoculture or multi-season cropping systems (Laborte et al., 2017) that accelerate soil nitrogen turnover, deplete inherent fertility, and necessitate greater external inputs(Cao et al., 2013; Y. Chen et al., 2018).

The spatial convergence of regions suitable for substantial nitrogen reduction and significant CH_4 emission mitigation through AWD creates implementation “hotspots,” particularly evident in the Lower Yangtze River Basin, Red River and Mekong deltas, central Thailand, and western Java. These priority zones typically feature moderate precipitation, acidic to neutral soil pH, and elevated SOC content, aligning with the optimal water-nitrogen coupling conditions identified in our mechanistic analysis (Section 4.2). This integrated spatial assessment provides a quantitative foundation for developing regionally differentiated implementation strategies that simultaneously address food security and climate mitigation objectives.

4.4. Study Limitations and Future Research Perspectives

Several uncertainties exist in our research findings. First, smallholder farming systems predominate within our study regions, where advanced agricultural technology adoption rates are limited (e.g., 22.2% for China) due to constraints in farmer demographics, field conditions, and infrastructure (B. Li et al., 2024). While our analysis focuses on experimental effectiveness under controlled conditions, this disparity may lead to overestimation of GHG mitigation potential for integrated management in practical applications (Cao et al., 2024). Therefore, future research should incorporate comprehensive socioeconomic assessment frameworks that evaluate adoption barriers and develop context-specific implementation strategies (Houlton et al., 2019; Yulong et al., 2021). Second, climate change considerations were not explicitly integrated within this analytical framework. Nevertheless, future research should incorporate predictive modeling approaches to assess management strategy robustness under projected environmental scenarios (Asseng et al., 2015; Yoo et al., 2025).

Additionally, most constituent studies encompass only single-season or short-term experimental periods (1–3 years), potentially precluding detection of long-term adaptive responses and cumulative synergistic effects. Sustained implementation of integrated management may elicit modifications in soil physicochemical properties, microbial community dynamics, and biogeochemical cycling processes that could alter observed synergistic relationships over extended timeframes. Comprehensive long-term experimental assessments (>5 years) represent critical future research priorities for validating temporal persistence of synergistic mechanisms (Lange et al., 2015; Smith et al., 2020; Yu et al., 2019). Despite these uncertainties, our proposed integrated water-nitrogen management provides evidence-based and actionable guidance for major Asian rice production regions, enabling simultaneous achievement of yield enhancement and GHG emission reduction while promoting agricultural sustainability.

5. Conclusions

Our meta-analysis of tropical and subtropical Asian rice systems demonstrates that integrating nitrogen fertilization with AWD irrigation produces significant synergistic benefits, simultaneously increasing yields and reducing GHG emissions, with maximum GHGI reduction at 180–270 kg N ha^{-1}. These effects are modulated by environmental factors, primarily soil pH, fertilizer type, precipitation, and SOC, with optimal outcomes in high-SOC, high-TN, acidic soils under moderate rainfall. Spatial analysis indicates that water-nitrogen management optimization can significantly reduce nitrogen inputs while maintaining yields and decreasing GHGI. These findings highlight that context-specific management strategies are crucial for simultaneously achieving increased productivity and climate mitigation in rice agroecosystems.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Climate data is available in Muñoz Sabater (2019). The Harmonized World Soil Database version 2.0 (HWSD v2.0) is available from FAO & IIASA (FAO & IIASA, 2023). Crop calendar data set is available in Jägermeyr et al. (2021). Global nitrogen application is available in X. Cui et al. (2021). The meta-analysis data set is available in the Zenodo repository (Wei et al., 2025).

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