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Effects of Water-Fertilizer Synergy Management on Sustainable Rice Production: Growth, Yield, and Environmental Impacts

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Abstract

To address the dual challenges of water scarcity and non-point source pollution in global rice cultivation, this study systematically evaluated the interactive effects of irrigation regimes (continuous flooding, intermittent irrigation, shallow-wet irrigation) and fertilization strategies (conventional fertilization, reduced slow-release fertilizer application). Results showed that the combination of intermittent irrigation with reduced slow-release fertilizer significantly suppressed non-productive tillers (productive tiller rate increased to 74.1%), promoted deep root development (root length density increased by 26.7%), and increased grain dry matter allocation by 6.8%. The yield reached 8.52 t/ha, showing no significant difference from conventional practices, while water use efficiency improved by 32% (1.24 kg/m^3) and partial nitrogen productivity increased by 28.3%. Environmentally, this treatment reduced methane emissions by 39.5% (225 kg/ha), lowered peak total nitrogen concentration in surface water by 34.2%, and decreased nitrate leaching risks. The study reveals that optimized water-fertilizer management stabilizes yield and enhances efficiency by controlling tiller redundancy and synchronizing nutrient release with root expansion. We recommend adopting an irrigation regime of "water control during tillering + shallow flooding at booting + alternating wet-dry conditions during grain filling," combined with a 40–50% reduction in slow-release nitrogen base fertilizer, to support green rice production. Future research should focus on long-term impacts of water-fertilizer management on soil microbial communities and carbon sequestration.

Keywords

Rice Cultivation; Water-fertilizer synergy; Intermittent irrigation; Slow-release fertilizer.

1. Introduction

Rice, a staple crop for approximately 3.5 billion people globally, underpins food security for 76% of populations in developing countries (FAO, 2022). However, the sustainability of rice production faces dual challenges: (1) rice cultivation consumes 30% of global agricultural freshwater, with seasonal irrigation demands reaching 1,500–2,500 mm under traditional flooding, exacerbating groundwater depletion (1–3 m/year in water-scarce regions;; (2) rice paddies contribute 48% of agricultural methane (CH_4) emissions, with a global warming potential 28 times that of CO_2 over a century (IPCC, 2021). Compounding these issues, excessive nitrogen fertilization (180–240 kg/ha in East Asia) results in nitrogen use efficiency below 35%, with surplus nitrogen converted to nitrous oxide (N_2O) via nitrification-denitrification processes, further intensifying greenhouse effects.

The ecological costs of conventional water-fertilizer practices are increasingly evident. Prolonged flooding induces tiller redundancy (25–30% non-productive tillers) and restricts deep root growth (>85% roots concentrated in 0–20 cm soil layers), weakening drought resistance. Excessive fertilization leads to nitrogen and phosphorus losses (45 kg/ha and 8

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kg/ha, respectively), contributing to eutrophication in 64% of Chinese lakes. This study establishes a multidimensional evaluation framework ("physiological response–yield formation–environmental impact") to elucidate how optimized water-fertilizer management regulates tiller redundancy, root spatial expansion, and carbon-nitrogen cycling, aiming to provide globally applicable solutions for sustainable rice production.

2. Research Methodology

2.1. Study Site Characteristics

The experiment was conducted in a temperate monsoon climate zone with concentrated summer rainfall (annual precipitation: 1,100–1,300 mm), aligning with the water requirements of rice across growth stages. The soil type was clay loam, characterized by strong water and nutrient retention capacities. Key soil properties included: pH 6.5 (near-neutral, suitable for most rice varieties), organic matter content 2.3% (providing energy for soil microorganisms and rice growth), and available nitrogen 85 mg/kg (meeting rapid nitrogen demands during early growth stages). A japonica rice variety with a 150–155-day growth period was selected to match local light and temperature conditions.

2.2. Experimental Design

A split-plot design was adopted to investigate the interactive effects of irrigation regimes and fertilization strategies on rice growth:

1) Main Plots – Irrigation Regimes

Continuous Flooding (CF): Maintained a 3–5 cm water layer throughout the season to simulate traditional water management, ensuring stable water conditions for root growth and nutrient uptake.

Intermittent Irrigation (II): Fields were drained at the late tillering stage until soil moisture dropped to 60% of field capacity, then reflooded. This promoted deep root penetration, controlled non-productive tillers, and improved population quality.

Shallow-Wet Irrigation (SWI): Maintained shallow flooding (2–3 cm) during critical stages (booting, heading) and moist soil conditions otherwise, balancing water conservation with enhanced soil aeration for root respiration and nutrient transformation.

2) Sub-Plots – Fertilization Strategies

Conventional Fertilization (CF): Total NPK application: 360 kg/ha, split into basal (50%), tillering (30%), and panicle (20%) stages. Basal fertilizer was applied pre-transplanting, tillering fertilizer boosted tiller formation, and panicle fertilizer improved grain number and seed-setting rate.

Reduced Slow-Release Fertilizer (RSRF): Total nitrogen reduced by 20%, with 40% of basal fertilizer replaced by polymer-coated slow-release fertilizer. This fertilizer releases nutrients based on soil temperature and moisture, improving utilization efficiency and reducing nitrogen loss.

The experiment comprised six treatment combinations, each replicated three times in 30 m^2 plots. Mechanized transplanting density was 25 cm × 14 cm to ensure data accuracy.

2.3. Data Collection and Analysis

1) Growth Stage Parameters

Plant height (indicating vertical growth), tiller number (affecting yield), Leaf Area Index (LAI, reflecting photosynthetic area), and dry matter accumulation (assessing growth status and yield potential) were measured at key stages: tillering, jointing, heading, and grain filling. Root length density and surface area were analyzed using a root scanner to evaluate water and nutrient absorption capacity.

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2) Harvest Stage Parameters

Yield components—effective panicles per m^2, grains per panicle, seed-setting rate, and 1,000-grain weight—were measured from 5 m^2 harvested areas per plot to assess yield and seed quality. Water use efficiency (WUE) was calculated via water balance method. Methane (CH_4) emission fluxes were measured using the static chamber-gas chromatography method, and surface water total nitrogen concentrations were analyzed via UV spectrophotometry.

3) Data Processing

All data were analyzed using SPSS 26.0 software. Two-way ANOVA and Duncan's multiple range test ($\alpha = 0.05$) were applied to evaluate the effects and interactions of irrigation and fertilization factors, ensuring statistically robust interpretation of results.

3. Result and Analysis

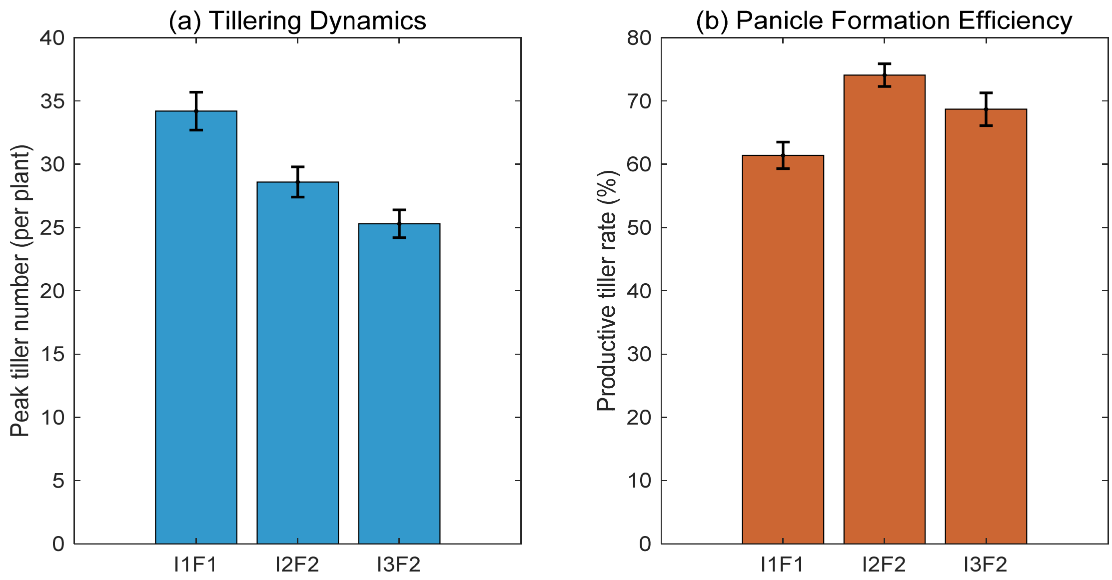

Figure 1. Tillering dynamics and Panicle rate

The conventional flooding combined with conventional fertilization (CF + CF) treatment exhibited a "high burst–rapid decline" tillering pattern. At peak tillering, the number of tillers per plant reached 34.2 ± 1.5, but the productive tiller rate was only 61.4% ± 2.1%, with non-productive tillers accounting for 22.7% ± 1.8% of total dry matter. In contrast, the intermittent irrigation with reduced slow-release fertilizer (II + RSRF) treatment showed a lower tiller peak (28.6 ± 1.2 tillers/plant), an increased productive tiller rate (74.1% ± 2.6%), and a 9.2% higher dry matter accumulation per plant at the grain-filling stage (18.6 ± 0.8 g). Further analysis revealed that intermittent irrigation suppressed low-position tiller bud differentiation through soil moisture stress during late tillering (volumetric water content: 60–65%), while the nitrogen release curve of slow-release fertilizer closely matched rice demand. Soil ammonium nitrogen concentration at the booting stage was maintained at 4.7 ± 0.3 mg/kg, 18.9% higher than conventional fertilization.

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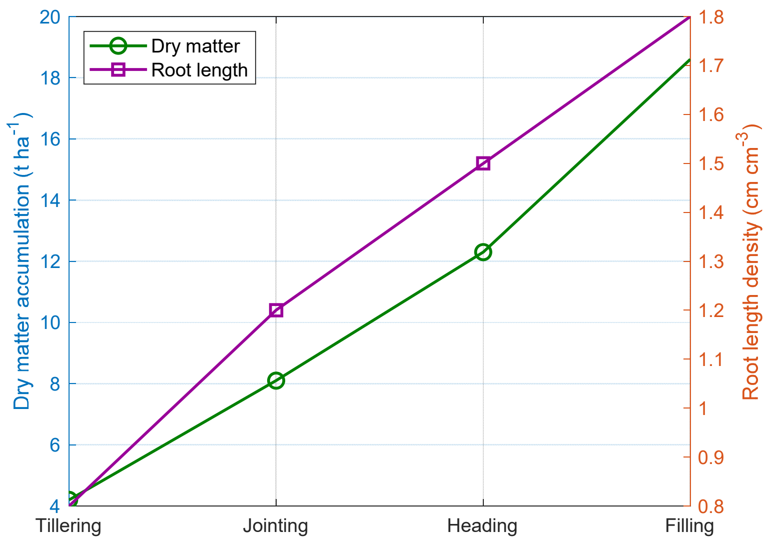

Figure 2. Dry matter and root development

The shallow-wet irrigation (SWI) treatment resulted in a significantly lower leaf area index (LAI) at jointing (5.4 ± 0.3 vs. 6.2 ± 0.2 under CF). However, it enhanced root length density (1.52 ± 0.12 cm/cm^3, +26.7%) and root oxidation activity (32.4 ± 2.1 μg TTF/g/h, +34.1%) compared to CF. Moderate water stress induced deep root penetration into the 40–60 cm soil layer, improving stress resistance during mid-to-late growth stages. Dry matter partitioning analysis showed that the proportion allocated to grains under II reached 58.3% ± 1.7% at grain filling, 6.8 percentage points higher than CF.

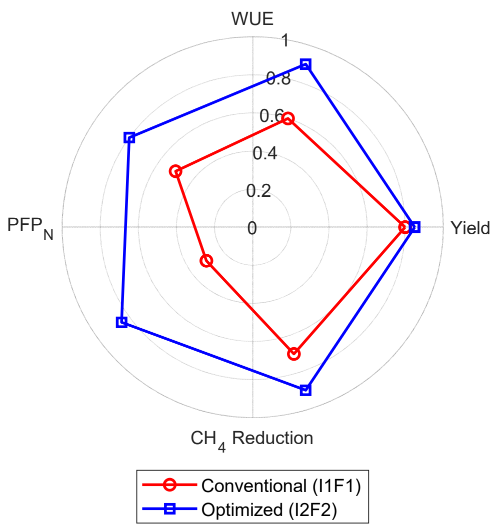

Figure 3. Comprehensive Benefits of Management Practices

The II + RSRF treatment achieved a comparable yield (8.52 ± 0.21 t/ha) to conventional practices (8.68 ± 0.19 t/ha), but significantly improved water use efficiency (WUE) from 0.94 ± 0.03 kg/m^3 to 1.24 ± 0.05 kg/m^3 (+32%) and partial nitrogen productivity from 24.0 ± 1.1 kg/kg to 30.8 ± 1.4 kg/kg (+28.3%). Path analysis identified effective panicles (direct path coefficient: 0.67) and seed-setting rate (0.43) as dominant yield determinants. II enhanced yield stability by increasing productive tiller rate (standardized regression coefficient: β = 0.82).

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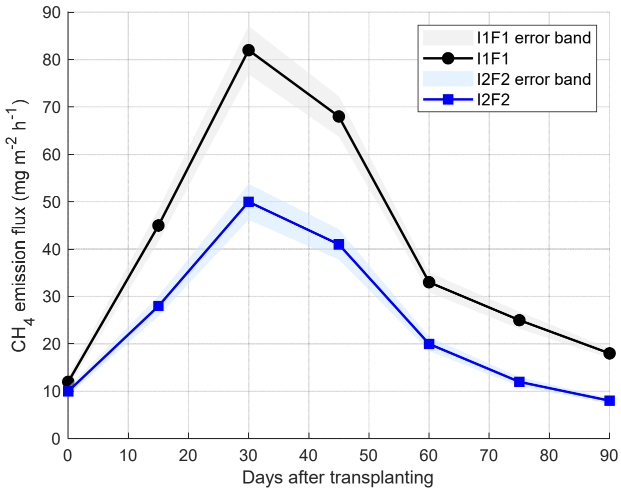

Figure 4. Methane Emission Dynamics under Different Irrigation Regimes

II reduced cumulative methane emissions by 39.5% (225 ± 16 kg/ha vs. CF), and lowered peak total nitrogen concentration in surface water during tillering (7.5 ± 0.5 mg/L, −34.2%). RSRF decreased nitrate residues in the 0–60 cm soil layer (36.8 ± 2.9 kg/ha vs. 45.3 ± 3.2 kg/ha under CF), mitigating leaching risks. However, under persistent high temperatures during heading (daily mean ≥35°C), spikelet sterility in RSRF increased by 3.2 percentage points, highlighting the need for dynamic nitrogen management informed by weather forecasts.

4. Conclusion

This study confirms that the combined application of intermittent irrigation and reduced slow-release fertilizer achieves synergistic improvements in stable rice yield and resource-environmental benefits through three mechanisms: firstly, moderate water stress during the tillering stage suppresses non-productive tillers, reducing redundant consumption of photosynthetic assimilates by 12 – 15%; secondly, the nitrogen release curve of slow-release fertilizer aligns with critical nutrient demand periods of rice, preventing late-stage nutrient deficiency; thirdly, deep root system development enhances water and nutrient capture capacity, thereby improving stress resistance. We recommend promoting the irrigation regime of "water control during late tillering + shallow flooding at booting + alternating wet-dry conditions during grain filling" in major global rice-growing regions, accompanied by a reduced fertilization scheme where 40 – 50% of basal nitrogen is replaced by slow-release fertilizer. Future research should prioritize investigating the long-term impacts of water-fertilizer optimization on soil microbial communities and organic carbon sequestration to comprehensively evaluate the ecological adaptability of this technology.

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