

Independent Effect of Water Regime and Fertilisers Treatments on GHG Emissions from Lowland Rice in West Java, Indonesia

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ABSTRACT

Lowland rice cultivation is a major contributor to agricultural greenhouse gas (GHG) emissions. Managing water and fertilizer is important GHG emissions. This paper evaluated GHG emissions of rice production under contrasting water regimes, i.e., continuous flooding (CF) versus alternate wetting and drying (AWD), with six nitrogen fertilizer combinations: no nitrogen (F1), urea 175 kg ha⁻¹ (F2), urea 350 kg ha⁻¹ (F3), urea 262.5 kg ha⁻¹ + manure 3 tons ha⁻¹ (F4), urea 525 kg ha⁻¹ + rice straw 3 tons ha⁻¹ (F5), and urea 175 kg ha⁻¹ + manure 3 tons ha⁻¹ + biochar 0.6 tons ha⁻¹ (F6). The field experiments were conducted at Bogor Regency, West Java, Indonesia, using a randomized complete block design with three replications. Growth, yield components, and GHG emissions were observed in this study throughout the growing season. Results showed AWD reduced CH₄ emissions by 30% but increased N₂O by 43% compared to CF, yielding a net 23% lower global warming potential (GWP). Organic-amended treatments (F6) maintained yields equivalent to conventional fertilization while showing numerically lower GWP. The independent effect of the water regime and the nitrogen fertilizer combinations implies that the best level of biochar and manure combined with AWD has the most promising prospect of maintaining rice yield while reducing GHG emissions.

Keywords: AWD, biochar, carbon sequestration, continuous flooding, manure

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INTRODUCTION

Mitigating greenhouse gas (GHG) emissions across multiple sectors, including agriculture, is a global calling to reduce global warming. Agricultural ecosystems have a major contribution to global GHG

emissions, accounting for 44% and 50% of anthropogenic CH₄ and N₂O emissions, respectively (Jia et al., 2019). Among agricultural practices, rice cultivation contributes to 10.1% of the total emissions from the agricultural sector and about 1.3–1.8% of the world's anthropogenic GHG emissions, primarily due to methane emissions (Wang et al., 2023). Simultaneously, global climate change is expected to negatively impact rice production under the global scenario, reducing rice yields by 0.6% to 1.2% by 2050 (Sun et al., 2023). Therefore, emission reduction in rice farming is important, while unscientific and unsustainable efforts may be increased to yield compensation (Ebrahimi et al., 2021; Souri & Hatamian, 2019).

Lowland rice farming mainly depends on saturated water management, which is called continuous flooding (CF). However, prolonged soil saturation promotes anaerobic microbial decomposition, producing methane. CF rice field stimulates complex methane emissions to the atmosphere due to the activity of methane-producing bacteria (methanogens) and methane-oxidizing bacteria (methanotrophs). Methane is produced at the final stage of anaerobic microbial organic material degradation, including materials from rice root exudates utilized by those microbes (Rajendran et al., 2023).

In Asia, CF rice cultivation uses about 80% of total irrigation water resources (Bin Rahman & Zhang, 2023). Water conservation techniques have been implemented, including alternate wetting and drying (AWD) that can reduce 38% of irrigation water usage without negatively impacting grain production (Gharsallah et al., 2023; Lampayan et al., 2015). Unlike CF, AWD implements alternating cycles of saturation (inundation) and unsaturation (drying), similar to intermittent irrigation implemented by IRRI (Mallareddy et al., 2023). AWD systems reduce percolation and seepage, thus reducing water use (Carrijo et al., 2017).

Livsey et al. (2019) and Mallareddy et al. (2023) found that AWD not only enhances water efficiency but also reduces GHG emissions. Ishfaq et al. (2020) estimated that implementing AWD reduces methane emissions by 11-95%. Thus, changing rice cultivation from CF to AWD reduces CH₄ emissions (Hoang et al., 2023). From a farmer's perspective, AWD is a simple and cheap technology for smallholders (Mallareddy et al., 2023).

While AWD is a promising mitigation strategy, nitrogen (N) fertilizer management is also important in optimizing rice production and minimizing GHG emissions. Excessive or inefficient application of N fertilizer can lead to increased N₂O emissions (Hou et al., 2024). In Indonesia, where rice farming is a crucial component of the country's agricultural sector, N fertilizer use is still suboptimal, with farmers often applying excessive or insufficient amounts (Susanti et al., 2024). Thus, combining AWD with a proper N fertilizer strategy can support sustainable rice farming by reducing CH₄ and N₂O emissions. However, there are trade-offs between CH₄ and N₂O emissions under AWD. While AWD reduces CH₄, at the same time, it increases N₂O emission (Gao et al., 2024). Therefore, discovering a suitable N fertilization strategy combined with AWD is critical to maximize its benefit.

This study compares CF and AWD water regimes with different N fertilizer applications. While AWD has been widely studied, its interaction with N fertilizer application remains an important area of research. According to the Food and Agriculture Organization of the United Nations (FAO) (2017), AWD can be considered a practical Climate-Smart Agriculture (CSA) practice that boosts agricultural productivity while lowering greenhouse GHG emissions. This study evaluates rice yields and the associated CH₄ and N₂O emissions under different water regimes and N fertilizer treatments.

MATERIALS AND METHODS

Experimental Site

This experiment was conducted from February 2024 to July 2024 at Cikarawang Experimental Field, Bogor, West Java, Indonesia (-6.5502208, 106.7290211). The yield component analysis was conducted at the Cikarawang Research Station, Department of Agronomy and Horticulture, Faculty of Agriculture, IPB. The GHG analysis was conducted at the Greenhouse Gas Laboratory of the Indonesian Agricultural Environment Standardization Institute, Central Java, Indonesia.

Experimental Design

This study used a split-plot Randomized Complete Block Design (RCBD) with two factors: irrigation treatment as the main plot and various combinations of N fertilizer doses with organic amendments as subplots. The water regime treatment consisted of continuous flooding (CF) and alternate wetting and drying (AWD), adapted from Lampayan et al. (2015). In CF, the water level was maintained at a 5–10 cm depth, except during fertilizer application and a week before harvest. In AWD, an initial 5–10 cm watering was applied and maintained until two weeks after transplanting (WAT). After this period, the water inlet was closed to stop water input, allowing the water level to decline gradually and initiating the wetting and drying cycle. The water inlet was opened when the water level dropped 15 cm below the ground surface to restore it to 5–10 cm above the surface. The re-flooding cycle lasts from about one day to more than 10 days after the water inlet is closed, depending on weather conditions, with longer periods if there is heavy rain. The water level below the soil surface was monitored by installing a perforated PVC pipe to allow water to seep into the pipe. The water inside the pipe was checked using a ruler stick.

The basic dose of N fertilizer followed the recommendation from the Regulation of Ministry of Agriculture No. 13/2022, namely the specific fertilization recommendation for the Dramaga location with a dose of urea fertilizer of 350 kg ha⁻¹, SP-36 100 kg ha⁻¹, and KCl 100 kg ha⁻¹ with the content for each fertilizer: 46% N, 36% P₂O₅ and 60% K₂O. The N fertilizer treatments consisted of six combinations, which integrated different N fertilizer doses with various organic materials, as detailed in Table 1.

Table 1
Treatments of N fertilizer combination

Code	N Fertilizer combination	Details
F1	No N fertilizer	Control
F2	Urea 175 kg ha ⁻¹	50% N recommended rate
F3	Urea 350 kg ha ⁻¹	100% N recommended rate
F4	Urea 262.5 kg ha ⁻¹ + manure 3 tons ha ⁻¹	75% N recommended rate supplemented with additional N from manure
F5	Urea 525 kg ha ⁻¹ + rice straw 3 tons ha ⁻¹	150% N recommended rate supplemented with N from rice straw decomposition
F6	Urea 175 kg ha ⁻¹ + manure 2.4 tons ha ⁻¹ + biochar 0.6 tons ha ⁻¹	50% N recommended rate supplemented with N from manure and biochar

Urea was applied in three split doses: one-third at 1 day after transplanting (DAT), another third at 7 DAT, and the remaining dose at 30 DAT. During field preparation, one month before transplanting, organic amendments, including manure, chopped rice straw (10 cm pieces), and rice husk biochar (pyrolyzed at 350°C), were incorporated into the soil to ensure proper decomposition and nutrient availability. Organic amendments were incorporated based on typical nutrient compositions reported by other studies: Manure: 1.06–2.77% N, 0.74–0.95% P, 0.34–1.25% K, 28.42–37.64% C (Alghifari et al., 2023; Sudarsono et al., 2014; Zhang et al., 2020); rice straw: 0.66–1.85% N, 0.09–1.8% P, 1.2–1.8% K, 39.9–44.4% C (Ali et al., 2024; Duan et al., 2015; Yan et al., 2019); rice husk biochar (350°C): 0.23% N, 0.08 % P, 0.48 % K, 44.32 % C. While the exact nutrient composition of manure and rice straw was not directly measured in this study, the reported ranges are based on data from relevant studies that reflect typical nutrient values for these materials under comparable conditions.

The experiment used 36 plots arranged in three replications, each measuring 7.5 m × 4.5 m and separated by 50 cm buffers to prevent treatment interference. The Inpari 32 rice variety was transplanted using 21-day-old seedlings at 20 cm × 20 cm spacing. A 1-meter border zone was maintained around each plot, with 10 representative hills randomly selected for sampling inside part of the border area to avoid border effects. The fertilization regime included full doses of phosphorus (P) and potassium (K) applied with the first urea split at 1 DAT, followed by additional urea applications at 7 DAT and 30 DAT. Manual weeding was performed throughout the growing season, while pest and disease control involved using carbofuran and mancozeb when necessary. Bird nets were installed at a height of 2 m during anthesis and remained until harvest to protect the crop during the critical stage. The rice was harvested at 110 DAT, with yield and biomass measurements taken from the sampled hills to evaluate treatment effects.

Measurements

Plant observation included plant height, tiller number per hill, and productive tiller number per hill. Yield components observation included panicle length, filled grains number per panicle, unfilled grains number per panicle, grains number per panicle, filled grains percentage, index of 1000-grain weight, harvest index, and yield per hectare. The calculation of harvest index was performed according to Du et al. (2022):

$$\text{Harvest index} = (\text{grain yield} / \text{aboveground dry matter accumulation})$$

GHG emissions of CH₄ and N₂O were measured, and Global Warming Potential (GWP) was calculated according to AR5 of IPCC. Gas sampling used a transparent closed chamber method (Setyanto et al., 2018) with some modifications. A fan-equipped chamber with dimensions of 0.5 m × 0.5 m × 1 m (L × W × H) was used for the experiment. At the top of the chamber, there is a hole covered with a septum (cover), which functions to take gas samples, and a hole to insert a thermometer sensor.

The gas sampling occurred three times per week, with additional sampling conducted for three days in a row following the N application. GHG sample was collected at 07.00-10.00 a.m. The chamber was installed on the third row of plant hills for each plot. The base chamber was installed from the first day of GHG sampling to the last day to maintain similar site until the end of the study.

Sampling was conducted simultaneously at 0, 15, and 30 minutes after the chamber was installed. The fan was turned on during sampling so that the air in the chamber became homogeneous, and the temperature was measured using a thermometer. A 20 mL syringe with a three-way stopcock is used to collect gas samples. The syringe was pumped for 2-3 injections to make the air inside homogeneous and then put into a 10 mL labeled glass vial. The vial was stored at room temperature before analysis. Gas samples were analyzed using gas chromatography (Varian 450-GC, Varian Inc., CA, USA) with a flame ionization detector and an electron capture detector for CH₄ and N₂O analysis, respectively.

Data Analysis

Statistical analysis of the data was carried out analysis of variance (ANOVA). For any treatments showing significant effects, Duncan's Multiple Range Test (DMRT) was performed at $\alpha=5\%$ across all parameters, except for GHG, which used $\alpha=10\%$ due to high uncertainty and variation in field GHG measurement. Pearson correlation analysis was conducted to analyze the relationships among parameters. All statistical tests were carried out using RStudio 4.4.1.

RESULTS

ANOVA Analysis

Analysis of variance did not show any significant effect of interaction between water management and N combination for all observed parameters (Table 2). Water management could significantly affect plant height at 8 WAT, panicle length, and grain weight per panicle, as well as CH₄ emission, N₂O emission, and GWP. In contrast, N combinations demonstrated broader effects, significantly affecting vegetative parameters (plant height, tiller numbers, and productive tillers), panicle length, grain development (filled/unfilled grain numbers, grain weights, and filling percentage), and GWP. In comparison, N combinations had no significant effect on CH₄ and N₂O emissions. Conversely, neither treatment significantly affected 1000-seed weight, grain yield per hectare, or the harvest index.

Table 2
Effects of water regime and N combination on agronomic and yield parameters of rice

Variable	Water regime (A)	N combination (B)	A × B
Plant height 8 WAT	*	**	ns
No. tillers 8 WAT	ns	**	ns
No. productive tillers per hill	ns	**	ns
Panicle length	*	*	ns
No. filled grains per panicle	ns	*	ns
No. unfilled grains per panicle	ns	*	ns
No. grains per panicle	ns	*	ns
Percentage of filled grains per panicle	ns	*	ns
Index 1000 seed	ns	ns	ns
Grain weight per panicle	*	*	ns
Grain weight per hill	ns	*	ns
Grain yield per ha	ns	ns	ns
Harvest index	ns	ns	ns
CH ₄	*z	ns	ns
N ₂ O	**	ns	ns
GWP	*z	*z	ns

Note. ** = significantly different at 0.01; * = significantly different at 0.05; *z = significantly different at 0.1 according to DMRT; ns = not significant

Plant Height and Number of Tillers

The plant responded differently to water regimes and N combination treatment throughout the vegetative space (Table 3). While early growth (2-4 weeks) showed no treatment differences, plants under CF grew taller than those under AWD by 6 WAT. Among N combination treatments, the manure-reduced urea combination (F4) produced plants as tall as those receiving full N recommendation rate and high N rate with straw treatments. Unfertilized

plants (F1) remained the shortest throughout the vegetative stage. In particular, reduced N rates combined with biochar and manure (F6) resulted in intermediate plant heights but were shorter than those combined with higher N rates and manure treatments (F4).

Tiller development showed different responses to treatments during the vegetative stage at 2–8 WAT (Table 4). AWD produced more tillers than CF at 4 WAT, although this difference was not observed at 6 and 8 WAT. All treatments showed a reduction in tiller numbers after the peak growth period at 4 WAT. The combination of N treatments significantly affected tiller production at particular times of the vegetative phase. The unfertilized control (F1) had fewer tillers than the fertilized treatments throughout the vegetative stage. In particular, the reduced

Table 3
Plant height at various water regimes and N fertilizer combinations at 2-8 weeks after transplanting (WAT)

Treatment	Plant height (cm)			
	2 WAT	4 WAT	6 WAT	8 WAT
Water regime				
CF	45.02	65.97	83.56 a	103.39 a
AWD	44.70	64.58	79.70 b	99.44 b
Significance level	ns	ns	*	*
N combination ha ⁻¹				
F1 (no N)	41.68	60.07	73.56 c	93.57 cd
F2 (urea 175 kg)	45.33	65.69	80.35 b	97.79 d
F3 (urea 350 kg)	44.75	64.69	80.73 ab	103.02 abc
F4 (urea 262.5 kg, manure 3 tons)	47.09	68.16	86.87 a	107.05 a
F5 (urea 525 kg, rice straw 3 tons)	45.81	68.10	85.89 ab	105.99 ab
F6 (urea 175 kg, manure 2.4 tons, biochar 0.6 tons)	44.52	64.94	82.38 ab	101.08 bc
Significance level	ns	ns	**	**

Note. Values within the same column marked with identical letters indicate no significant difference based on DMRT, ** = significantly different at 0.01, * = significantly different at 0.05, ns = not significant

Table 4
Tiller number per hill at various water regimes and N fertilizer combinations at 2-8 weeks after transplanting (WAT)

Treatment	Tiller number			
	2 WAT	4 WAT	6 WAT	8 WAT
Water regime				
CF	13.08	22.40 b	21.41	18.66
AWD	12.73	24.69 a	21.30	17.54
Significance level	ns	*	ns	ns
N combination ha ⁻¹				
F1 (No N)	12.13	20.13 b	17.57 b	15.22 b
F2 (urea 175 kg)	12.75	22.69 ab	20.46 a	16.10 b

Table 4 (continue)

Treatment	Tiller number			
	2 WAT	4 WAT	6 WAT	8 WAT
F3 (urea 350 kg)	13.42	24.55 a	23.38 a	20.42 a
F4 (urea 262.5 kg, manure 3 tons)	13.50	25.08 a	22.77 a	18.79 a
F5 (urea 525 kg, rice straw 3 tons)	12.10	25.57 a	22.85 a	18.89 a
F6 (urea 175 kg, manure 2.4 tons, biochar 0.6 tons)	13.53	23.23 ab	21.13 a	19.18 a
Significance level	ns	*	**	**

Note. Values within the same column marked with identical letters indicate no significant difference based on DMRT, ** = significantly different at 0.01, * = significantly different at 0.05, ns = not significant

N rate treatment with manure and biochar (F6) had similar tiller numbers to the full N rate (F3) and the other organic-amended treatments (F4–F5) at 8 WAT. At 4 WAT, the treatments combining N with organic inputs (F4–F5) showed numerically higher tiller numbers than the other treatments, although statistically similar to the conventional high-N rate approach (F3) and the low-N combined with biochar and manure (F6). This suggests organic amendments can increase early tillering production without requiring full N recommended doses.

Yield Component

The water regime significantly affected panicle length but not productive tiller number, with CF producing longer panicles than AWD (Table 5). N fertilizer combinations affected both parameters, with the full N recommendation rate treatment (F3) and all that combined organic amendment treatments (F4-F6) producing more productive tillers than plots with no N or lower N rates (F1-F2), with no statistical difference among the best performing groups. For panicle length, the N-enriched treatments (F3-F6) outperformed the unfertilized control (F1), with all organic-added combinations (F4-F6) matching the performance of the conventional full N recommendation rate (F3). Particularly, the reduced N rate treatment supplemented with manure and biochar (F6) achieved an equivalent tiller number and panicle length compared to the full N rate (F3) and higher N rate fertilizer combinations (F4-F5) despite using 50% less urea than F3.

The combination of N fertilizer significantly affected all yield component parameters except 1000-seed weight, while the water regime showed no significant effect on grain characteristics (Table 6). The combination of reduced N rate with manure and biochar (F6) resulted in the number of filled grains and its percentage equivalent to the high N rate with straw treatment (F5) for filled grains and higher than the unfertilized control (F1) and some treatments with relatively lower N levels (F2, F4). In particular, all N-amended treatments except F2 and F4 matched the performance of F6 in total grain number. The 1000-seed weight remained uniform across all treatments since this study used one variety, indicating that the treatment did not affect individual grain weight.

Table 5
Number of productive tillers and panicle length at different water regimes and N fertilizer combinations

Treatment	No. productive tillers per hill	Panicle length (cm)
Water regime		
CF	12.89	20.82 a
AWD	12.89	19.98 b
Significance level	ns	*
N combination ha ⁻¹		
F1 (No N)	9.61 c	19.04 b
F2 (urea 175 kg)	11.68 b	20.05 ab
F3 (urea 350 kg)	14.38 a	20.64 a
F4 (urea 262.5 kg, manure 3 tons)	13.72 a	20.88 a
F5 (urea 525 kg, rice straw 3 tons)	14.37 a	20.88 a
F6 (urea 175 kg, manure 2.4 tons, biochar 0.6 tons)	13.59 a	20.88 a
Significance level	**	*

Note. Values within the same column marked with identical letters indicate no significant difference based on DMRT, ** = significantly different at 0.01; * = significantly different at 0.05; ns = not significant

Table 6
Number of filled, unfilled, total, percentage of filled grains per panicle, and index 1000 seed at different water regimes and N fertilizer combinations

Treatment	Number of grains per panicle				Index 1000 seed (g)
	Filled	Unfilled	Total	Filled grains (%)	
Water regime					
CF	68.52	30.31	96.88	70.70	28.14
AWD	61.30	28.35	91.62	67.35	28.37
Significance level	ns	ns	ns	ns	ns
N combination ha ⁻¹					
F1 (No N)	58.52 b	21.26 b	79.78 b	72.23 ab	28.07
F2 (urea 175 kg)	59.35 b	32.85 a	92.20 ab	64.29 b	27.64
F3 (urea 350 kg)	66.75 ab	34.10 a	100.84 a	66.79 ab	28.05
F4 (urea 262.5 kg, manure 3 tons)	57.52 b	33.30 a	90.82 ab	63.49 b	28.58
F5 (urea 525 kg, rice straw 3 tons)	71.82 ab	27.99 ab	99.81 a	72.26 ab	27.83
F6 (urea 175 kg, manure 2.4 tons, biochar 0.6 tons)	75.52 a	26.51 ab	102.03 a	75.13 a	29.35
Significance level	*	*	*	*	ns

Note. Values within the same column marked with identical letters indicate no significant difference based on DMRT, * = significantly different at 0.05; ns = not significant

The water regime significantly affected grain weight per panicle, with CF producing heavier grains per panicle than AWD but not grain weight per hill (Table 7). N combinations affected grain weight per panicle and hill, where treatments combining N with organic amendments (F5-F6) performed statistically equivalent to the conventional full N rate (F3) in panicle weight with higher yields compared to the unfertilized treatment (F1) and the lower N rate and manure treatments (F2, F4). In particular, F6 (lower N with manure and biochar) performed similarly to F5 (high N with straw) in both panicle and hill grain weight despite using 50% less inorganic N input. No significant differences were found in grain yield per hectare or harvest index across treatments. This result indicates that those water regimes resulting similar yields, even though AWD uses less water.

Table 7
Grain weight per panicle and hill, grain yield, and harvest index at different water regimes and N fertilizer combinations

Treatment	Grain weight (g)		Grain yield (ton ha ⁻¹)	Harvest index
	per panicle	per hill		
Water regime				
CF	1.84 a	13.63	4.13	0.46
AWD	1.61 b	11.70	4.11	0.45
Significance level	*	ns	ns	ns
N combination ha ⁻¹				
F1 (No N)	1.56 b	9.83 b	3.54	0.43
F2 (urea 175 kg)	1.59 b	10.84 ab	4.15	0.45
F3 (urea 350 kg)	1.77 ab	14.77 ab	3.79	0.47
F4 (urea 262.5 kg, manure 3 tons)	1.53 b	10.41 ab	4.24	0.48
F5 (urea 525 kg, rice straw 3 tons)	1.89 ab	15.42 a	4.24	0.41
F6 (urea 175 kg, manure 2.4 tons, biochar 0.6 tons)	2.01 a	15.10 a	4.77	0.47
Significance level	*	*	ns	ns

Note. Values within the same column marked with identical letters indicate no significant difference based on DMRT, * = significantly different at 0.05; ns = not significant

GHG Emission

Water regime treatments significantly affected GHG emissions (Table 8). CF produced higher CH₄ emissions than AWD, while AWD produced more significant N₂O emissions than CF. Despite these opposing patterns, AWD showed a reduction in GWP relative to CF due to methane’s more significant and dominant contribution to the overall GWP value.

Nitrogen management strategies showed a more limited effect on individual gas emissions. No significant differences were observed among N treatments for either CH₄ or N₂O. However, some variation in GWP was observed, with conventional high-N

Table 8
Total emissions of CH₄ and N₂O, and GWP of rice plants at different water regimes and N fertilizer combinations

Treatment	CH ₄ (kg CH ₄ ha ⁻¹)	N ₂ O (kg N ₂ O ha ⁻¹)	GWP (kg CO _{2eq} ha ⁻¹)
Water regime			
CF	148.22 a	1.62 b	4578.73 a
AWD	103.78 b	2.31 a	3518.81 b
Significance level	**	***	*z
N combination ha ⁻¹			
F1 (No N)	86.04	1.6	2833.82 b
F2 (urea 175 kg)	140.94	2.0	4475.78 ab
F3 (urea 350 kg)	144.67	2.11	4609.06 a
F4 (urea 262.5 kg, manure 3 tons)	121.64	2.08	3956.72 ab
F5 (urea 525 kg, rice straw 3 tons)	145.14	2.29	4669.79 a
F6 (urea 175 kg, manure 2.4 tons, biochar 0.6 tons)	117.56	1.72	3747.82 ab
Significance level	ns	ns	*z

Note. Values within the same column marked with identical letters indicate no significant difference based on the DMRT test. *** = significantly different at 0.01; ** = significantly different at 0.05; *z = significantly different at 0.1; ns = not significant at 0.1

treatments (F3–F5) higher than the control (F1), with lower N rate treatments showing more moderate effects (F2, F4, and F6), and the unfertilized control (F1) having the lowest GWP. This trend hints at the potential to reduce GHG emissions through N fertilizer management, particularly in treatments that combine reduced inorganic N inputs with organic amendments.

Correlation Analysis

Pearson correlation analysis revealed the pattern of relationships between vegetative growth, yield components, and environmental parameters (Figure 1). Vegetative growth parameters showed time-dependent relationships with yield components. Tiller number at 8 WAT (TN8) was more strongly correlated with productive tillers (r = 0.73) and had a weak correlation with yield (r = 0.39) than earlier tiller numbers (TN2-TN6), showing that late vegetative tiller number is critical for productivity. In contrast, plant height (PH2-PH8) showed a weaker correlation with yield (r = 0.04–0.26) but a moderate correlation with panicle length (r = 0.19–0.46).

On the other hand, a significant positive relationship was observed between traits related to grain production, including filled grains (FG) along with grain weight per panicle (GPW) and grain weight per hill (GHW). These results showed that the rice’s ability at the grain-filling stage substantially affected yield potential. In particular, grain weight per panicle

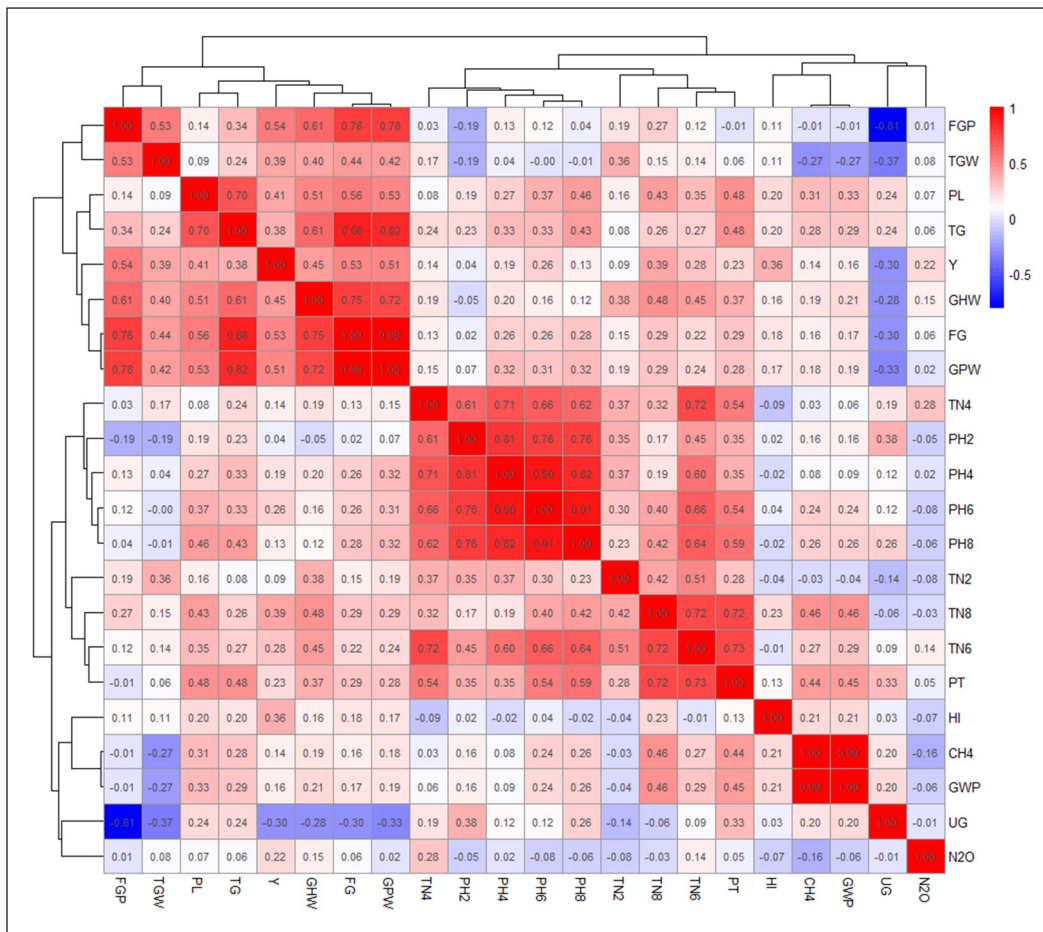


Figure 1. Correlation patterns among growth, yield, and greenhouse gas parameters of rice plants at different water regimes and N fertilizer combinations

Note. PH2 = Plant height at 2 WAT; PH4 = Plant height at 4 WAT; PH6 = Plant height at 6 WAT; PH8 = Plant height at 8 WAT; TN2 = Tiller number at 2 WAT; TN4 = Tiller number at 4 WAT; TN6 = Tiller number at 6 WAT; TN8 = Tiller number at 8 WAT; PT = Num. of productive tiller; PL = Panicle length; FG = Num of filled grain per panicle; UG = Num of unfilled grain per panicle; TG = Total num of grain per panicle; FGP = Filled grain percentage; GPW = Grain per panicle weight; GHW = Grain per hill weight; TGW = 1000 grain weight; Y = Yield per ha; HI = Harvest index; CH4 = CH₄ emission; N2O = N₂O emission; GWP = GWP

(GPW) showed a very strong correlation with FG ($r = 0.99$), while its relationship with yield per hectare was moderate ($r = 0.51$). Unfilled grain (UG) showed a slight negative correlation with grain weight (GHW/GPW; $r = -0.28$ to -0.33), indicating that resource allocation during grain filling is related to the source-sink balance.

GHG emissions parameter formed a separate cluster from the other clusters, showing a relatively insignificant direct relationship with morphological traits, especially in the early growth phase. However, plant height and number of tillers at 8 WAT showed an increasing

trend in the relationship with GHG emissions over time. This study also found a very strong correlation between CH₄ emissions and GWP ($r = 0.99$), which showed that most of the GWP contributors to lowland rice cultivation are dominated by CH₄.

DISCUSSION

Rice Growth and Yield

This study showed different responses to water regime treatments and N fertilizer combinations at different stages of growth. CF produced taller plants at 8 WAT while in the peak vegetative phase than AWD. This also happens in similar studies by Khairi et al. (2015). Other crops also show a pattern in other irrigated crops, including taro and maize (Hidayatullah et al., 2020; Ramadhani et al., 2024). However, the early tillering phase showed the opposite pattern, with AWD producing more tillers than CF at 4 WAT. This result contrasts previous reports (Khairi et al., 2015) and may indicate variability in our experimental condition in newly developed lowland land. The subsequent tillering senescence observed between 4–8 WAT, more in F3 (fully synthetic N) and F6 (organic reduced N), may indeed be related to the process of asynchronous tillering (Kariali et al., 2012) and variable of N mineralization in newly developed soils.

Water availability significantly affects panicle development through several pathways. Continuous flooding conditions in CF can increase cell elongation and nutrient uptake (Chen et al., 2024), while periodic drying in AWD may optimize resource allocation to reproductive structures. The treatment that combined a low N rate with manure and biochar (F6) resulted in comparable grain-filling performance to the increased N application rate. This led to equal filled grains and percentage of filled grains per panicle (Table 6). Organic amendments work in synergy with minimal nitrogen inputs to reduce expenses associated with inorganic nitrogen usage. Studies confirm that biochar can enhance nutrient-holding capacity (Xie et al., 2022), and manure releases nitrogen gradually for crop needs (Ebrahimi et al., 2021; Zhou et al., 2022).

The findings proved that water conservation through AWD could match conventional flooding irrigation yields and reduce water usage. Using AWD water conservation techniques helps decrease production expenses in pump irrigation systems while maintaining crop yields, leading to possible economic benefits. A study by Johnson et al. (2023) showed that AWD yield levels were sometimes lower than CF, but the results of Rahman and Bulbul (2014) showed higher yields than CF. Our study found similar yield levels between AWD and CF systems, similar to the study by Howell et al. (2015). This variation in yield is thought to be due to genotype-environment interactions, as rice exhibits plasticity in resource allocation depending on its environment (Kumar et al., 2022).

Promoting AWD Practice

Numerous studies have examined the effects of AWD on rice cultivation, but it is still an attractive area of research. The inconsistency and variability in research outcomes, mainly yield and GHG emissions under AWD, present an interesting subject for further study. Location and country-level variation in AWD performance due to differences in genetics and environment suggest further investigation. In the present research, the AWD water regime produced an insignificant difference in rice grain yield to CF (Table 7), which is in line with the findings reported by Howell et al. (2015). Nevertheless, AWD experiments often resulted in inconsistent rice yield. According to Khairi et al. (2015) and Johnson et al. (2023), AWD decreases rice yield more than conventional flooding systems, while Rahman and Bulbul (2014) reported increasing rice yield. Generally, rice yield is determined by genetic and environmental factors (Agusta et al., 2022; Dulbari et al., 2021). Kumar et al. (2022) further highlighted that rice has molecular plasticity that determines the response to environmental conditions, allowing it to adapt to environmental conditions.

In this study, AWD was recharged nine times throughout the experiment, while CF was recharged daily. In this study, AWD resulted in an estimated 62% reduction in irrigation water use compared to CF. Given that there was no significant interaction between the water regime and N treatment (Table 2), AWD presents a viable option for improving water-use efficiency in rice cultivation while maintaining yield, particularly in regions with limited water resources.

In Indonesia, lowland rice can be planted in three planting seasons in a year. However, using the continuous flooding system that farmers have widely used, the available irrigation water is usually only sufficient for two planting seasons. The transition from CF to AWD can increase water availability due to water saving, which has the potential to allow for additional planting seasons, as shown in Bangladesh (Hossain & Islam, 2022).

Moreover, AWD has shown significant potential in reducing GHG emissions from rice fields (Table 8). In the present study, GWP decreased by 23.15%, and CH₄ emissions decreased by 29.98% under AWD relative to CF. It is important to note that AWD practice increased N₂O emission by about 42.59%. Since the impact of N₂O and CH₄ relative to CO₂ are 265 times and 28 times, respectively, controlling N₂O emission under AWD is important. Hassan et al. (2022) recommended many methods to mitigate N₂O emission, i.e., 1) increase soil pH by lime application, 2) reduce soil moisture by proper tillage, 3) increase soil temperature by applying bacterial population, 4) adding cereal straw with higher C:N ratio, 5) application of side banding N than broadcasting and deeper layer, 6) increase soil depth of plowing to reduce soil microorganism activity, 7) manage the proportion of sandy soil to maximize soil texture, 8) modification of irrigation system, 9) apply less tillage, 10) crop residue management, 11) use slow release N and proper amount, 12) selecting suitable fertilizers, 13) biochar application, 14) use nitrification inhibitors, 15) use organic amendments such as manure and fermented organic manure, 16) apply arbuscular

mycorrhizal fungi, 17) selecting plant genotype, 18) crop rotation, and 19) integrated nutrient management of inorganic fertilizers and organic amendment. Furthermore, Cheng et al. (2024) revealed that the selection of plowing equipment significantly decreased soil bulk density while enhancing soil redox potential and reducing GWP by 10.7-28.6%.

The significantly higher CH₄ emissions observed under CF (Table 8) can be attributed to anaerobic conditions that favor methanogenic bacteria. These bacteria do not use oxygen and produce methane as the final product. In contrast, AWD disrupts continuous anaerobic conditions, which leads to a decrease in CH₄ emission. More than 90% of CH₄ is released through plant-mediated transport via aerenchyma (Bhattacharyya et al., 2016). A recent study suggests that reducing aerenchyma formation in rice plants through genetic modification has shown potential in mitigating CH₄ emissions by limiting oxygen diffusion and altering methanotroph diversity in the rhizosphere (Iqbal et al., 2020). However, as aerenchyma is an important structure in oxygen transport to the root zone, limiting aerenchyma might affect the survival rate of rice in flooded environments.

On the other hand, AWD showed higher N₂O emissions than CF (Table 8), as alternating wet and dry conditions enhance nitrification-denitrification processes, key pathways for N₂O production. Previous studies have noted that N₂O emission increases up to 18–280% in AWD relative to CF (Liao et al., 2020; Liu et al., 2023). Nevertheless, the present research shows that AWD had 42.59% more N₂O emissions but 23.15% lower GWP than CF. Other studies have reported a relatively more expansive range of GWP reductions under AWD, which ranged from 13% to 41% (Hossain & Islam, 2022; Islam et al., 2020; Pramono et al., 2022). The results show that AWD indeed can reduce GHG emissions, but the exact level of reduction cannot be ascertained.

Fertilizer Management to Mitigate GHGs

The combination of N fertilizers with organic amendments influences various effects on GHG emissions and GWP (Table 8). The GWP of the treated field (F2 to F6) was higher than the control (F1). Treatments of F3 and F5 showed the highest GWP, highlighting the substantial contribution of CH₄ emissions to the overall GWP. In contrast, F1 (control no N fertilizer) had the lowest GWP, followed by F6, which combined biochar and manure with moderate urea levels (50% of the recommended dose). Although still an early indication, biochar application can potentially reduce CH₄ and N₂O emissions.

Moreover, Hassan et al. (2022) reported that adding biochar can improve the soil's physical, biological, and chemical characteristics with a very slow decomposition process. Their study observed that biochar application was associated with lower N₂O emissions, potentially due to increased soil pH. The biochar derived from rice husks used in this research has enhanced soil carbon sequestration without significantly increasing GHG emissions (Koyama et al., 2015, 2016).

Due to high data variability (data not shown), no statistically significant differences were found between N fertilizer combination treatments for CH₄ and N₂O emissions. However, F1 tends to have a low CH₄ emission trend due to the absence of additional N and organic matter. On the other hand, a high CH₄ emission trend was found in treatments with higher N levels, such as F3 and F5 (Table 8). Li et al. (2022) also reported that increasing N fertilizer doses generally led to higher CH₄ emissions, especially at higher application rates. This increase could be attributed to the increased N input and organic matter as the substrate for methanogenesis.

Similarly, while N₂O emissions did not differ significantly among the treatments (Table 8), an increasing trend was observed from F1 to F2 to F3. At the same urea application rate (F2 vs. F6), the manure and biochar supplementation slightly reduce N₂O, though this reduction is not statistically significant. The highest N₂O emission was found in F5 (the highest level of urea application rate), indicating an increasing nitrification process. Since there is no interaction between the water regime and the N fertilizer combinations (Table 2), the F6 treatment appears promising for further evaluation due to the lower urea requirement and reduced GHG emissions. In their review, Hassan et al. (2022) emphasized that to mitigate N₂O substantially, the application of biochar at a rate larger than 5 tons ha⁻¹ is common. Future studies should explore higher biochar application levels and reduced urea rates to optimize GHG mitigation.

Moreover, Table 7 shows that the F6 treatment resulted in the same grain production per hill as F5, the highest urea application rate in this study. These results suggest that reducing urea rates while combining it with organic amendments (manure and biochar) can provide the same grain production results as higher urea rates while potentially reducing GHG emissions, hence offering economic and environmental benefits. However, further long-term studies are required to confirm its effectiveness (Lee et al., 2024). Thus, incorporating biochar into fertilizer management may effectively reduce GHG emissions while reducing farmers' costs since biochar can be made from agricultural waste.

Correlation Analysis of Growth, Yield, and Emission Variables

The Pearson correlation and hierarchical clustering analysis showed the relationships between plant morphological traits, yield components, and GHG emissions (Figure 1). The dendrogram separated the variables into three main groups: (i) morphological traits, including plant height (PH) and tiller number (TN) during the vegetative stage, and (ii) yield components, such as panicle length (PL), number of productive tillers (PT), filled grains per panicle (FG), total grains per panicle (TG), grain weight per hill (GHW), and grain yield (Y). (iii) GHG emissions, including GHG emissions and GWP. Interestingly, CH₄ and N₂O emissions, as well as GWP, formed subgroups that tended to separate.

The correlation matrix showed that early plant growth variables (PH2, TN2) showed weak correlations with yield-related traits. However, the relationship between these variables and yield increased over time as the plant progressed through vegetative growth, especially for tiller number (TN) in the vegetative phase before shifting to the reproductive phase. The number of productive tillers (PT) observed before harvest showed a stronger positive correlation with filled grains per panicle (FG; $r = 0.72$) and grain yield (Y; $r = 0.76$), indicating the importance of productive tiller capacity in determining rice productivity. Previous studies have reported that the maximum tiller number is one of the main determinants of yield, with high-yielding tillers contributing significantly to yield (Martinez-Eixarch et al., 2015). In contrast, unfilled grains per panicle (UG) and grain yield (Y) had a negative correlation, indicating that fertilization failure during the anthesis phase may affect final grain yield. Thus, minimizing sterility during this phase is important to maximize the total grain yield. Therefore, ensuring optimal environmental conditions and nutrient availability minimizes sterility and maximizes yield (Raharimanana et al., 2023).

Regarding GHG emissions, CH₄ showed a strong correlation with GWP ($r = 0.99$), confirming its dominant role in total emissions from rice cultivation. Other studies reported that CH₄ contributes about 71.9 to 86.1% of the total GWP from the rice growing period (Naser et al., 2020). However, in this study, CH₄ had only moderate correlations with plant morphological traits, especially with late-stage vegetative phase variables such as PH8 ($r = 0.42$) and TN8 ($r = 0.38$). This suggests that methane emissions are influenced by the physiological status of rice plants at later stages, possibly due to increased aerenchyma formation that facilitates methane transport. As rice plants mature, root biomass, shoot architecture, and aerenchyma development are crucial in regulating methane production and oxidation (Rajendran et al., 2023). In contrast, N₂O emissions showed relatively weak correlations with plant growth parameters, indicating that N₂O emissions are driven more by external factors such as soil properties and N fertilization than plant traits. This underscores the importance of an integrated assessment of soil, water, and fertilization management to understand better and mitigate N₂O emissions in agricultural systems (Carbonell-Bojollo et al., 2022).

Yield-related parameters showed weak to moderate correlations with CH₄ and N₂O emissions, showing that the increase in rice yield does not necessarily result in increased emissions. This finding also showed an opportunity to optimize water and N management strategies to achieve higher yields while minimizing emissions. Strategies used in this study, such as AWD and biochar application, have a promising potential to minimize environmental impacts without yield penalties. Other studies found that practices like AWD irrigation can reduce methane emissions without yield loss (Tarlera et al., 2015), biochar enhances soil fertility and carbon sequestration (Xu et al., 2022) and optimized N

application maximizes yields while reducing yield-scaled GWP by 21% (Pittelkow et al., 2014). These findings suggest further investigation and integration with other low-emission practices to optimize sustainable rice farming.

CONCLUSION

This study found that alternate wetting and drying water regimes can reduce CH₄ emissions by 30% while at the same time increasing N₂O emissions by 43% compared to continuous flooding. However, the total GWP of alternate wetting and drying was 23% lower than that of continuous flooding, reducing the environmental impact. Most importantly, these benefits came without significantly compromising rice growth and yield and combining half the recommended urea dosage with manure 2.4 tons ha⁻¹ and biochar 0.6 tons ha⁻¹ produced yields comparable to conventional high-nitrogen treatments while showing the potential to reduce climate impacts. Since water regime and nitrogen fertilizer combinations had an independent effect, applying alternate wetting and drying irrigation with lower dosages of urea combined with 2.4 tons ha⁻¹ and biochar 0.6 tons ha⁻¹ may offer a promising approach for the sustainable reduction of GHG emissions and maintaining rice production yield. Further research on biochar's long-term benefits under local conditions needs to be investigated.

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