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Integrated Plant Nutrient Systems Improve Rice Yields without Affecting Greenhouse Gas Emissions from Lowland Rice Cultivation

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Abstract: Efficient management of fertilizers and irrigation could mitigate greenhouse gas (GHG) emissions and increase crop yields. Field experiments were conducted to determine the effects of an integrated plant nutrient system (IPNS) and water regime—alternate wetting and drying (AWD) and continuous flooding (CF)—on GHG emissions and rice yield. Fertilizer treatments included control (no N), prilled urea (PU), urea deep placement (UDP), and IPNS (50% N from poultry litter and 50% N from PU). Gas sampling and analysis were performed using a closed-chamber technique and gas chromatography. IPNS produced significantly ($p < 0.05$) higher seasonal total methane (CH_4) emissions (9–15%) compared to the UDP treatment, but the emissions with IPNS were similar to those of PU. IPNS had an interaction effect with the water regime on nitrogen oxide (N_2O) emissions. IPNS produced more emissions than PU under AWD, but their emissions were similar under CF irrigation. IPNS produced a significantly higher total global warming potential (GWP) than UDP but a GWP similar to the PU treatment in both Aus (pre-monsoon) and Aman (wet) seasons. AWD irrigation reduced the total GWP by 8% over CF without yield reductions. IPNS significantly increased rice yields compared to broadcast PU but yields were similar to those of UDP. These findings suggest that both IPNS and UDP could be effective in increasing crop yields without increasing GHG emissions.

Keywords: alternate wetting and drying; Bangladesh; greenhouse gases; integrated plant nutrient system; methane; nitrous oxide; urea deep placement

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1. Introduction

Rice (*Oryza sativa*) is a staple food for 160 million people in Bangladesh. It is grown on approximately 11.4 million hectares (ha) of land in three rice-growing seasons–Boro (dry: December/January to April/May), Aus (pre-monsoon: April/May to July/August), and Aman (wet: July/August to November/December)–with a total production of 36.6 million metric tons (mt) in 2020 [1]. Bangladesh produced 7% of the world's 503.17 million mt of rice, ranking third behind China (29.5%) and India (23.8%) [1]. Rice covered 1.1 million ha and 5.6 million ha in Aus and Aman, producing 2.8 million mt and 14.2 million mt, respectively, in Bangladesh [1].

Globally, rice cultivation is considered one of the major anthropogenic sources of methane (CH_4) and nitrous oxide (N_2O) emissions. Both CH_4 and N_2O are serious greenhouse gases (GHGs) that contribute to global warming by trapping heat in the atmosphere. In a 100-year time horizon, CH_4 has a global warming potential (GWP) of 28, while the GWP of N_2O is 265 times that [2]. Emissions of these gases could be affected by different soil, climatic, and nutrient management factors [3,4]. Some of the important factors include excessive or imbalanced use of nitrogen (N) fertilizer and inappropriate management of irrigation water and crop residues. Emissions can be mitigated by following good agricultural practices, including improved management of fertilizers and irrigation regimes [3–5].

Inefficient management of N fertilizer not only affects crop productivity, but also increases N losses, including greenhouse gas emissions [6,7]. In contrast, an efficient N fertilizer application method, such as urea deep placement (UDP), can substantially improve rice yield and nitrogen use efficiency (NUE) [7,8] and reduce GHG emissions [5,9,10]. However, the effects of UDP across different irrigation and fertilizer regimes under different rice-growing seasons have yet to be studied.

Excessive and imbalanced application of chemical fertilizers can result in atmospheric pollution and affect soil health [6,7,11]. This issue is more critical in the current context of increasing fertilizer prices in the global market due to COVID−19 and the Russia–Ukraine conflict. Therefore, fertilizers should be applied judiciously, particularly by maintaining a proper combination of organic and inorganic inputs, so that both soil fertility and crop productivity can be improved with minimal effects on atmospheric pollution [5,12–15]. Application of organic inputs, including crop residues, manures, and compost, improves soil fertility and crop productivity by increasing carbon sequestration and mineralization of nutrients in the soil [13–17]. Organic inputs improve the soil's physical, chemical, and biological properties, resulting in an increased nutrient supply to plants [12,18]. Locally available organic inputs, such as poultry litter, supply carbon (C) and N in soils consistently throughout the crop-growing period, which helps to increase crop productivity and sustainably maintain soil health [13–15]. Use of organic residues may also decrease nutrient loss by leaching [19], but a larger application rate is required, due to their lower nutrient density compared to chemical fertilizers, to match the crops nutrient requirements, and this may reduce the rice yield [13,14]. Therefore, an appropriate ratio of inorganic fertilizers and organic inputs could be more effective in meeting the plant's nutrient demand and improving rice yield and soil fertility [12,15]. It has been reported that continuous use of organic inputs can alter the GHG emissions from soil [4,11,17,20–23], though it has been revealed that integrated use of poultry litter and prilled urea (PU) as an IPNS could improve soil fertility and crop yields [13,24] without increasing GHG emissions [5,13,14]. Similarly, the incorporation of organic inputs, such as biochar, could maintain soil fertility without increasing GHG emissions [21,22]. However, studies on the effects of IPNSs, particularly the use of poultry litter in combination with conventional N fertilizer urea, on GHG emissions across different water regimes are limited.

The effects of fertilizer management practices on yields and GHG emissions vary by water regime. Thus, improving water management can significantly reduce GHG emissions without affecting crop yield. For example, AWD irrigation in rice cultivation reduces CH_4 emissions by up to 30% compared to conventional irrigation [3,5,25,26]. In contrast, it can increase N_2O emissions compared to conventional irrigation. However, this increase could be compensated for by a decrease in CH_4 emissions [27–31]. The studies on the effects of fertilizer management under AWD irrigation are still inconsistent, although this technology could improve root morphology and soil enzymatic activities and maintain the N balance between NH_4^+/NO_3^-, which improves NUE [32,33]. In contrast, some reports have shown that AWD irrigation stimulates N losses through leaching and denitrification of N_2O [5,29,33]. Therefore, more studies are needed across different fertilizer management practices under various irrigation regimes to ensure sustainable rice production and maintain soil health while mitigating GHG emissions.

This study was conducted to determine the effects of an IPNS on GHG emissions as well as rice yields across two water regimes—AWD and CF—as compared with the improved N application method of UDP and conventional N management with PU. Field trials were conducted during the Aus and Aman (wet) seasons of 2018, 2019, and 2020 in Bangladesh to investigate the effects of UDP and IPNS treatments on rice yields and GHG emissions as a function of two different irrigation regimes.

2. Materials and Methods

2.1. Description of the Study Site

The study site at Bangladesh Rice Research Institute, Gazipur, Bangladesh, is located at latitude 23°59′25′′ and longitude 90°24′33′′. The experiments were conducted during the Aus (pre-monsoon) and Aman (monsoon) wet seasons in 2018, 2019, and 2020. The Aus season lasts from April/May to July/August, while the Aman season lasts from July/August to November/December. Rice cultivation during these seasons is mostly rainfed. Supplemental irrigation may be required in the first few months of Aus and in the last few months of the Aman season. The mean air temperature in Bangladesh is generally 25 °C. Mean rainfall is about 2000 mm per year, mostly occurring from June to September. Figure 1 depicts the average daily temperature and rainfall during the rice-growing season. Table 1 displays the soil's physicochemical parameters prior to the start of the studies.

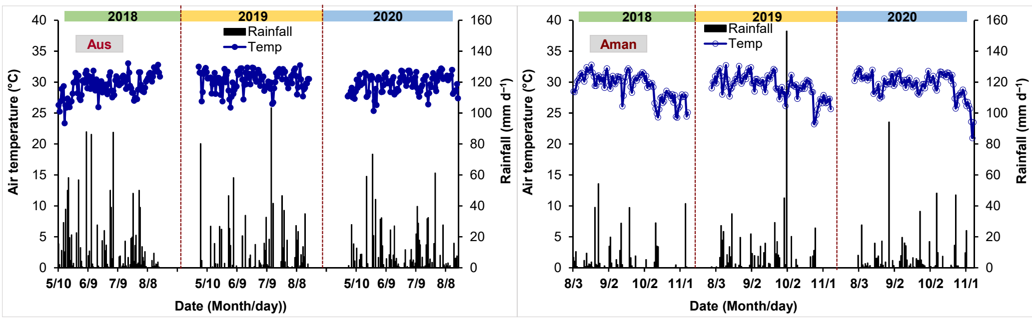

Figure 1. Daily average precipitation, air temperature, and solar radiation during the trial period in the Boro season of 2018, 2019, and 2020. (Data source: Weather station, Bangladesh Rice Research Institute, Gazipur).

Table 1. Soil properties before the start of the experiment.

Soil Properties	Value	Analysis Method
pH-H_2O	6.13	1:2.5 (soil:water) [34]
Organic carbon (%)	1.31	Wet oxidation [35]
Total N (%)	0.16	Kjeldahl [36]
Available P (mg kg^{-1})	12.65	0.5 M $NaHCO_3$ extracted [37]
Available K ($cmol_c$ kg^{-1})	0.12	Neutral 1.0 N NH_4OAc extraction [38]
Available S (mg kg^{-1})	9.31	$Ca(H_2PO_4)_2$ extraction [38]
Available Fe (mg kg^{-1})	565.5	DTPA extraction [38]
Available Mn (mg kg^{-1})	69.4	DTPA extraction [38]
Available Zn (mg kg^{-1})	14.3	DTPA extraction [38]
Particle size (%)		- [39]
Sand	29.96	
Silt	40.10	
Clay	29.94	

2.2. Treatments, Experimental Design, and Crop Management

Experimental treatments were a combination of two water regimes (main plot), i.e., AWD and continuous flooding (CF), and four fertilizer treatments (sub-plots). The four fertilizer treatments were (i) control at 0 kg N ha^{-1}; (ii) UDP at 52 kg N ha^{-1}; (iii) broadcast application of prilled urea (PU) at 52 kg N ha^{-1}; and (iv) IPNS, consisting of a combination of poultry litter and PU at 52 kg N ha^{-1}. These treatment combinations were arranged in a split-plot design with three replications. The size of each experimental plot was 4.8 m × 3.2 m.

For the UDP treatment, one 1.8-g urea briquette (a physically compressed form of PU) was applied at 8–10 cm depth at the center of four rice hills. Spacing of briquette application was 40 × 40 cm. With this geometry of application, there were 62,500 placement sites per hectare. UDP was applied 8 days after rice transplanting, when puddled soil was settled.

The entire amount of PU was broadcast twice at 7–10 days after transplanting (DAT) and 25–30 DAT due to the short growth duration of the rice variety. For the IPNS treatment, PU provided 50% of the N (26 kg) and poultry litter provided the remaining 50% (26 kg). During the last stages of land preparation, well-decomposed poultry litter (1.21% N, 1.15% P, and 0.91% K) was mixed into the soil.

Seedlings of popular rice varieties, i.e., BRRI dhan65 and BRRI dhan62, were transplanted at a distance of 20 cm × 20 cm in the Aus and Aman seasons, respectively. Crop management practices, including fertilizer management, specifically split application of N fertilizer, and weed management were followed as per government recommendations. Phosphorus (triple superphosphate) and potassium (muriate of potash) fertilizers were applied during final land preparation as basal fertilizers in all plots at 15 kg P ha^{-1} and 50 kg K ha^{-1}. In addition, 12 kg S ha^{-1} as gypsum and 1 kg Zn ha^{-1} as zinc sulfate were applied to all plots as basal fertilizers.

Two weeks before harvest, all of the plots under CF conditions were irrigated continuously, whereas the AWD plots were irrigated using the safe AWD approach [40]. At 10 DAT, perforated PVC pipe was placed into each AWD plot at a 15 cm depth to monitor floodwater. AWD plots were irrigated when the water level in the PVC pipe dropped 12–15 cm below the soil surface (Figure 2). Although the floodwater depth was monitored regularly to schedule irrigation and maintain the AWD cycle, the monsoon rain interrupted the AWD cycle. Nonetheless, after application of a topdressing of PU and at the flowering stage, plots under both the AWD and CF practices were kept constantly submerged for a week.

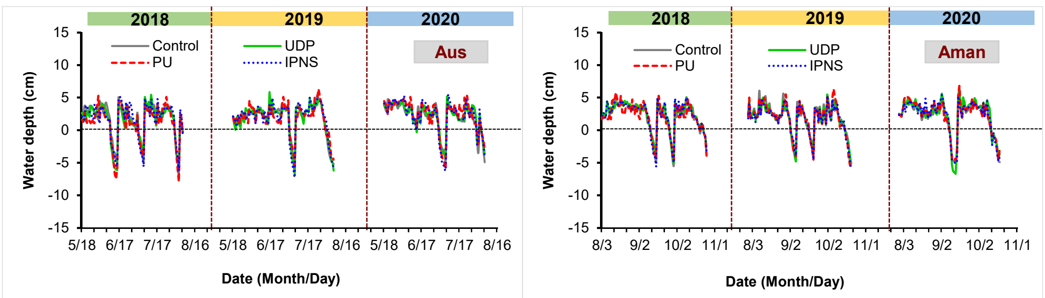

Figure 2. Daily floodwater depth across different fertilizer treatments under AWD conditions in Aus and Aman.

2.3. Gas Sampling and Analysis

A detailed gas sampling technique, described by Islam et al. [3], was used. In short, air samples were taken to measure CH_4 and N_2O emissions using a closed-chamber sampling method. Each closed chamber consisted of the base (70 L) and the chamber (216 L). The acrylic sheet used for the chamber's top (lid) and the base has a metal frame. Installed permanently in the rice field at a depth of 8–10 cm, each chamber foundation covered six rice hills and was left there throughout the rice-growing season. Water was used as a sealant between the chamber top and bottom during each gas sampling session. A battery-powered fan was installed in each gas chamber to ensure that the air inside the chamber was mixed uniformly. The temperature within the chamber was measured with a thermometer in order to calculate the CH_4 and N_2O emission rates. Gas samples were collected every week using a 50-milliliter airtight syringe with a three-way stopcock. A pipette tip with a three-way stopcock was connected to the chamber wall. Three gas samples were taken at 15-min intervals (0, 15, and 30 min) for each sampling period. A butyl rubber septum was used to seal the 30-milliliter air-evacuated glass vials containing the gas samples for laboratory examination.

A gas chromatograph (Shimadzu GC-2014, Kyoto, Japan), equipped with a flame ionization detector and an electron capture detector, was used to determine the concentrations of CH_4 and N_2O in the collected samples. A column was filled with Porapak Q (Tokyo, Japan) (80–100 mesh) and kept at 50 °C. For flame ionization detection and electron capture detection, the detector was heated to 150 °C and 300 °C, respectively. For the study of CH_4 and N_2O, the carrier gases N_2 and Ar were utilized. For CH_4 analysis, H_2 and air were employed as the combustion and supporting gases, respectively.

2.4. Estimation of CH_4 and N_2O Emissions

Emission rates were calculated using the slope of linear regression curves of the gas concentrations (CH_4 and N_2O) versus chamber close time. The slope of linear regression was corrected for temperature, pressure, chamber volume, and area covered. The emission rates were expressed as mg m^{-2} day^{-1}.

2.5. Data Analysis

Data on cumulative CH_4 and N_2O emissions, GWP, greenhouse gas intensity (GHGI), and rice yields were analyzed using the STAR 2.0.1 program from the International Rice Research Institute (IRRI), Los Baños, Philippines. Using a split-plot framework, ANOVA was conducted with irrigation regimes as the main plot and fertilizer treatments as the sub-plot. Normality and homogeneity of variance were tested before running the ANOVA. Tukey's honest significant difference test was used to compare the mean values of treatments in a pairwise comparison with a 5% probability.

3. Results

3.1. CH_4 Emissions

The temporal variations in CH_4 emissions across all treatments and years are presented in Figure 3a–l for Aus and Aman, respectively. Generally, emission rates showed a decreasing trend after the flowering stage. The IPNS treatment showed relatively large emission peaks compared to UDP but peaks similar to those of the PU treatment. CH_4 emission peaks declined rapidly during the dry period for all treatments and seasons (Figure 3a–l).

Cumulative CH_4 and emission factors (EFs) were significantly ($p < 0.05$) affected by fertilizer treatment in both the Aus and Aman seasons (Tables 2 and 3). IPNS significantly increased total emissions and EFs compared to the UDP treatment but similar to those of the PU treatment in both Aus and Aman seasons. Water management had significant ($p < 0.05$) effects on emissions and EFs. AWD irrigation reduced cumulative CH_4 emissions by 8% in Aus (Table 2) and 9% in Aman (Table 3) compared to CF conditions. The EF of CH_4 was 1.76 and 1.92 kg ha^{-1} day^{-1} (average across fertilizers and years) under AWD and CF irrigation, respectively, in the Aus season (Table 2), while it was 1.79 and 1.96 kg ha^{-1} d^{-1} under AWD and CF irrigation, respectively, in the Aman season (Table 3).

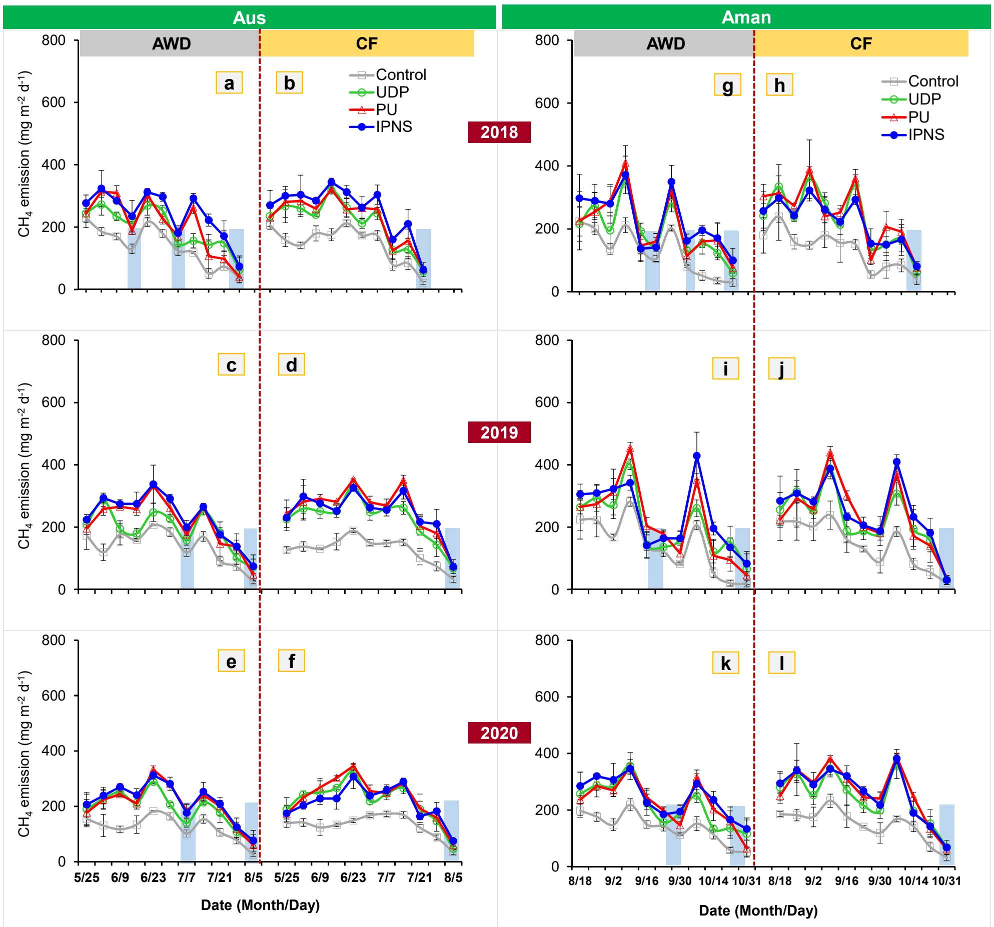

Figure 3. Variations in CH_4 emission rates under AWD and CF irrigation at the BRRI farm in Gazipur, Bangladesh, throughout the Aus (**a**–**f**) and Aman (**g**–**l**) seasons in 2018, 2019, and 2020. UDP, urea deep placement; PU, prilled urea; IPNS, integrated plant nutrient system. The shaded area represents the amount of time required for drying. Vertical bars indicate the standard error of the mean (n = 3).

Table 2. Effects of fertilizer treatments, year and irrigation regimes on CH_4 and N_2O emissions and emission factors (EFs), global warming potential (GWP), and greenhouse gas intensity (GHGI) in the Aus season.

Fertilizer Management	**Year**	**CH_4 Emission (kg ha^{-1})**	**EF of CH_4 [a] (kg ha^{-1} d^{-1})**	**N_2O Emission (g ha^{-1})**	**EF of N_2O [a] (g ha^{-1} d^{-1})**	**GWP [b]**	**GHGI [c]**
			Means of 2 Water Regimes				
			Effect of fertilizer treatments				
Control-N0	Mean	98.6 c	1.22 c	24.1 b	0.30 b	2769.6 c	1.01 c
UDP-N52		153.2 b	1.90 b	142.7 a	1.77 a	4348.0 b	1.24 b
PU-N52		167.2 a	2.07 a	144.5 a	1.79 a	4742.8 a	1.59 a
IPNS-N52		175.5 a	2.18 a	155.3 a	1.92 a	4979.2 a	1.38 b
			Effect of year				
Mean	2018	150.9 a	1.89 a	93.33 b	1.17 b	4263.3 a	1.30 a
	2019	152.1 a	1.88 a	130.13 a	1.61 a	4312.0 a	1.34 a
	2020	142.9 a	1.76 a	126.46 a	1.56 a	4054.5 a	1.26 a

Table 2. *Cont.*

Fertilizer Management	Year	CH_4 Emission ($kg\ ha^{-1}$)		EF of CH_4 [a] ($kg\ ha^{-1}\ d^{-1}$)		N_2O Emission ($g\ ha^{-1}$)		EF of N_2O [a] ($g\ ha^{-1}\ d^{-1}$)		GWP [b]		GHGI [c]	
		Means of 2 Water Regimes											
		Effect of irrigation regimes											
		AWD	CF	AWD	CF	AWD	CF	AWD	CF	AWD	CF	AWD	CF
Mean	Mean	142.1 B	155.2 A	1.76 B	1.92 A	126.5 A	106.8 B	1.57 A	1.32 B	4031.4 B	4388.5 A	1.24 B	1.36 A
ANOVA (*p* values)													
Irrigation (I)		0.0439		0.0463		0.0298		0.0298		0.0468		0.0049	
Fertilizer (F)		0.0000		0.0000		0.0000		0.0000		0.0000		0.0000	
Year (Y)		0.0008		0.0004		0.1290		0.1466		0.0007		0.3452	
I × F		0.2072		0.2054		0.0562		0.0563		0.2178		0.2418	
I × Y		0.9297		0.9298		0.9156		0.9174		0.9267		0.9747	
F × Y		0.3487		0.3393		0.0992		0.1114		0.3482		0.1290	
I × F × Y		0.8950		0.9018		0.9914		0.9907		0.8866		0.8204	

Within a column, means followed by the same lowercase letters, and within a row for each response variable, means followed by the same uppercase letters are not significantly different at a 5% level of probability by Tukey's honest significant difference test. UDP, urea deep placement; PU, prilled urea; IPNS, integrated plant nutrient system. [a] EF of CH_4 and N_2O was calculated by dividing total CH_4 and N_2O emissions by the active rice growth period (days). [b] GWP (kg CO_2 equivalent ha^{-1}) of CH_4 and N_2O was calculated using GWP of 28 and 265 for CH_4 and N_2O, respectively [2]. [c] GHGI (kg CO_2 equivalent kg^{-1} grain yield) was calculated by dividing total GWP by grain yield ($kg\ ha^{-1}$).

Table 3. Effects of fertilizer treatments, water regimes and year on CH_4 and N_2O emissions and emission factors (EFs), global warming potential (GWP), and greenhouse gas intensity (GHGI) in the Aman season.

Fertilizer Management	Year	CH_4 Emission ($kg\ ha^{-1}$)	EF of CH_4 [a] ($kg\ ha^{-1}\ d^{-1}$)	N_2O Emission ($g\ ha^{-1}$)		EF of N_2O [a] ($g\ ha^{-1}\ d^{-1}$)		GWP [b]	GHGI [c]
		Mean of 2 Water Regimes	**Mean of 2 Water Regimes**	**AWD**	**CF**	**AWD**	**CF**	**Mean of 2 Water Regimes**	**Mean of 2 Water Regimes**
		Fertilizer and irrigation regimes interaction							
Control-N0	Mean	102.6 c	1.24 c	66.8 d	59.2 c	0.81 d	0.71 c	2898.9 c	0.83 c
UDP-N52		164.1 b	1.98 b	261.5 b	173.1 b	3.15 b	2.09 b	4683.8 b	1.07 b
PU-N52		175.6 a	2.12 a	208.3 c	227.1 a	2.51 c	2.74 a	5007.9 a	1.24 a
IPNS-N52		179.2 a	2.16 a	322.7 a	262.7 a	3.89 a	3.17 a	5139.1 a	1.14 ab
		Effect of year							
Mean	2018	147.5 b	1.76 b	181.6 b		2.16 b		4204.7 b	1.03 b
	2019	155.5 a	1.87 a	196.3 a		2.37 a		4436.1 a	1.05 ab
	2020	163.1 a	1.99 a	215.1 a		2.62 a		4656.5 a	1.13 a

Table 3. *Cont.*

Fertilizer Management	Year	CH_4 Emission (kg ha^{-1})		EF of CH_4 [a] (kg ha^{-1} d^{-1})		N_2O Emission (g ha^{-1})		EF of N_2O [a] (g ha^{-1} d^{-1})		GWP [b]		GHGI [c]	
		Mean of 2 Water Regimes		Mean of 2 Water Regimes		AWD	CF	AWD	CF	Mean of 2 Water Regimes		Mean of 2 Water Regimes	
Effect of irrigation regimes													
		AWD	CF	AWD	CF	AWD	CF	AWD	CF	AWD	CF	AWD	CF
Mean	Mean	148.1 B	162.6 A	1.79 B	1.96 A	214.8 A	180.5 B	2.59 A	2.18 B	4236.7 B	4628.2 A	1.03 B	1.12 A
ANOVA (*p* values)													
Irrigation (I)		0.0027		0.0026		0.0086		0.0086		0.0035		0.0060	
Fertilizer (F)		0.0000		0.0000		0.0000		0.0000		0.0000		0.0000	
Year (Y)		0.0056		0.0021		0.0786		0.0487		0.0042		0.0442	
I × F		0.3041		0.2994		0.0046		0.0047		0.2919		0.6445	
I × Y		0.7861		0.7580		0.5763		0.5925		0.7759		0.7386	
F × Y		0.9046		0.8779		0.9734		0.9714		0.8997		0.9414	
I × F × Y		0.9602		0.9598		0.8258		0.8193		0.9622		0.9629	

Within a column, means followed by the same lowercase letters, and within a row for each response variable, means followed by the same uppercase letters are not significantly different at a 5% level of probability by Tukey's honest significant difference test. [a] EF of CH_4 and N_2O was calculated by dividing total CH_4 and N_2O emissions by the active rice growth period (days). [b] GWP (kg CO_2 equivalent ha^{-1}) of CH_4 and N_2O was calculated using GWP of 28 and 265 for CH_4 and N_2O, respectively [2]. [c] GHGI (kg CO_2 equivalent kg^{-1} grain yield) was calculated by dividing total GWP by grain yield (kg ha^{-1}).

3.2. N_2O Emissions

The temporal variations in N_2O emissions across all treatments and years are presented in Figure 4a–l for Aus and Aman, respectively. N_2O emission peaks were irregular and event-specific throughout the rice-growing season. In general, emission peaks were observed only after topdressing with N fertilizer or during the dry period. For the AWD practice, emission peaks were found in both the drying and fertilization period, while in CF conditions, emission peaks were observed only during fertilization in both Aus and Aman seasons (Figure 4). Some emission peaks were observed after harvesting the crop in all fertilizer treatments. Across years and fertilizer treatments, N_2O emissions ranged from −0.17 to 1.30 mg N m^{-2} day^{-1} under AWD irrigation and from −0.16 to 1.65 mg N m^{-2} day^{-1} under CF conditions during the Aus season (Figure 4a–f). Similarly, they ranged from −0.21 to 1.84 mg N m^{-2} day^{-1} under AWD irrigation and from −0.13 to 1.78 mg N m^{-2} day^{-1} under CF conditions during the Aman season (Figure 4g–l).

Fertilizer treatments had significant ($p < 0.05$) effects on total N_2O emissions and EFs in both Aus and Aman seasons (Tables 2 and 3). In the Aus season, emissions and EFs of PU, UDP, and IPNS treatments were similar. In the Aman season, N_2O emissions and EFs were higher for the IPNS treatment compared to PU under AWD irrigation, while they were similar under CF conditions (Table 3). However, the total N_2O emissions and EFs of UDP were lower than the IPNS treatment under both water regimes (Table 3). In contrast to CH_4 emissions, the cumulative N_2O emissions from AWD irrigation increased by 18% in the Aus season (Table 2) and by 19% in the Aman season (Table 3) compared to CF irrigation.

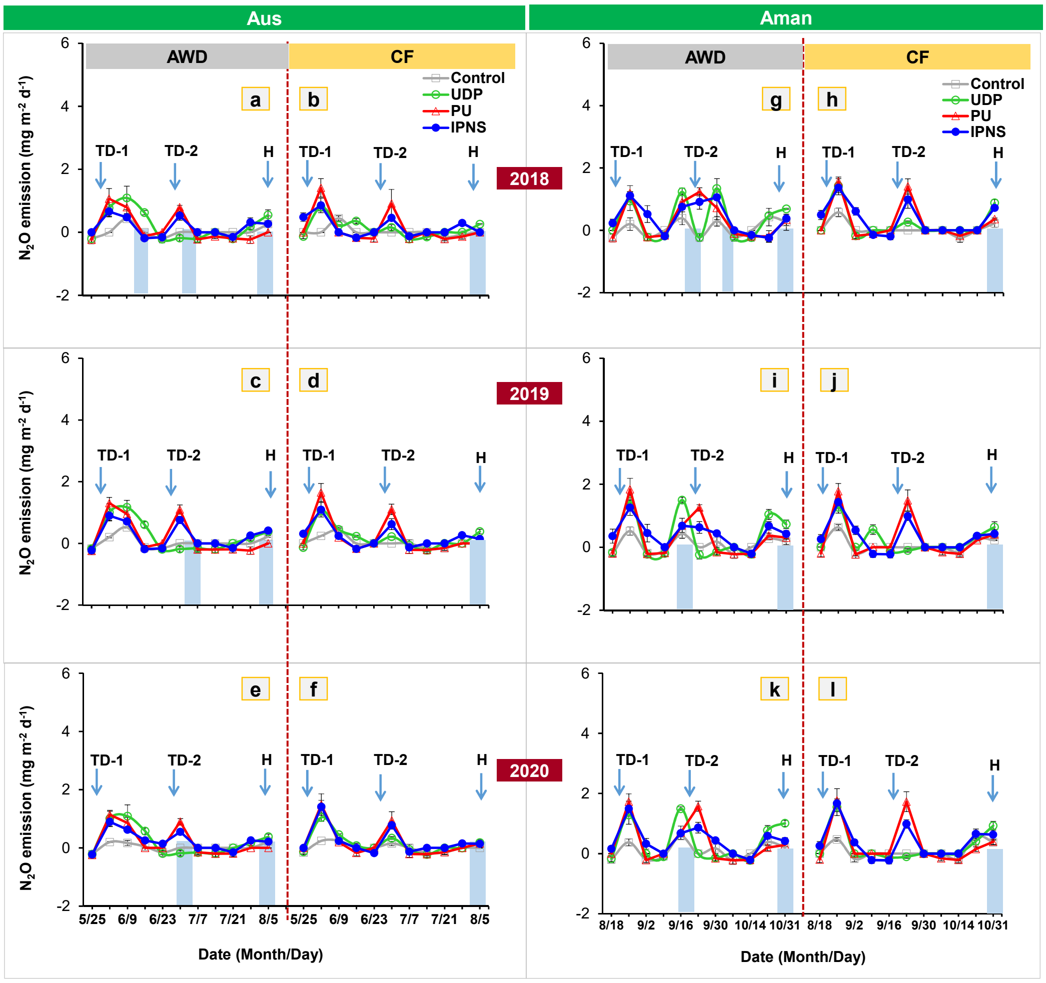

Figure 4. Variations in N_2O emission rates under AWD and CF irrigation at the BRRI farm in Gazipur, Bangladesh, throughout the Aus (**a**–**f**) and Aman (**g**–**l**) seasons in 2018, 2019, and 2020. T, transplanting; TD-1, first topdressing; TD-2, second topdressing; H, harvesting; UDP, urea deep placement; PU, prilled urea; IPNS, integrated plant nutrient system. The shaded area represents the amount of time require for drying. Vertical bars indicate the standard error of the mean (n = 3).

3.3. GWP and GHGI

UDP significantly ($p < 0.05$) reduced GWP by 8% and 13% in the Aus season (Table 2) and 6% and 9% in the Aman season compared to PU and IPNS, respectively (Table 3). The IPNS treatment showed a GWP similar to PU (Tables 2 and 3). However, the IPNS treatment significantly ($p < 0.05$) reduced GHGI compared to PU (Tables 2 and 3). Across the years and fertilizer treatments, AWD irrigation significantly ($p < 0.05$) decreased GWP by 8% in the Aus season and 9% in the Aman season compared to CF conditions. Similarly, the AWD practice reduced GHGI by 9% in the Aus season and 8% in the Aman season compared to CF irrigation.

3.4. Grain and Straw Yield

The fertilizer treatments showed a significant ($p < 0.05$) effect on grain and straw yield (Figure 5). IPNS significantly ($p < 0.05$) increased grain yield compared to PU in both Aus and Aman seasons (Figure 5). However, UDP showed responses similar to the IPNS treatment in both seasons. Water regime had no significant ($p > 0.05$) effect on grain and straw yield (Figure 5). Across fertilizer treatments and years, no significant variation in rice yield between the two irrigation regimes (AWD and CF) was observed (Figure 5).

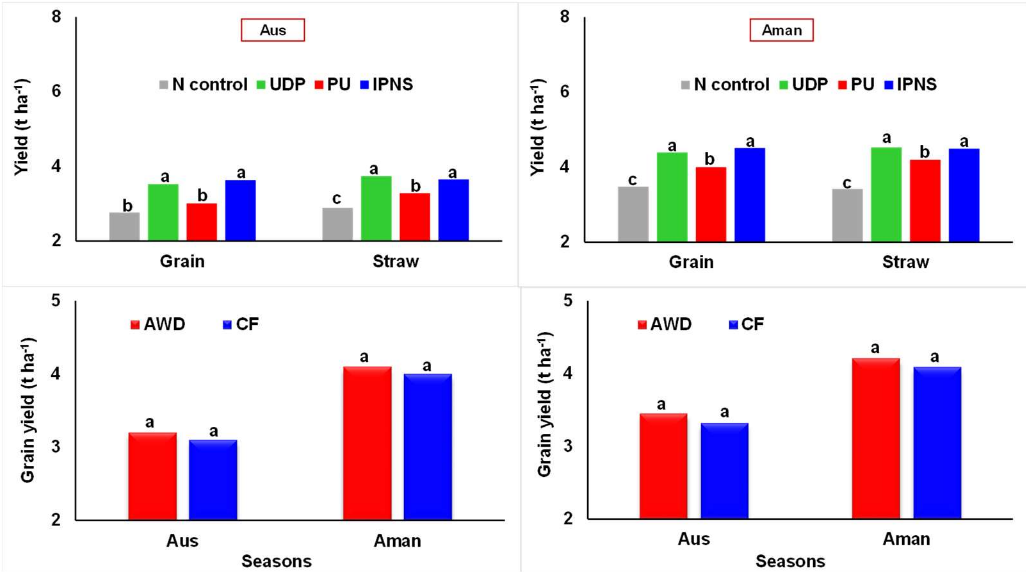

Figure 5. Effect of fertilizer and water management practice on rice yield in the Aus and Aman seasons (values are means across years). UDP, urea deep placement; PU, prilled urea, IPNS, integrated plant nutrient system; CF, continuous flooding; AWD, alternate wetting and drying. Means followed by the same letters within response variable and season are not significantly different at a 5% level of probability by Tukey's honest significant difference test.

4. Discussion

4.1. CH_4 Emissions

N fertilizer management and water regime play a major role in mitigating CH_4 emissions from rice cultivation. The temporal pattern of CH_4 emissions as affected by fertilizer and water regimes is well documented [3,5]. Generally, two to three emission peaks appear throughout the rice-growing season and emission rates decline after the maturity stage (Figure 3a–l). The declining emission rate at maturity stage could be associated with a lower photosynthesis rate and decreasing transport capacity of the aerenchyma channel [41]. In this study, the higher emissions under the IPNS and PU treatments compared to UDP are consistent with previous studies [5,11,42]. The higher emissions for IPNS could be due to the increased supply of labile carbon from poultry litter, which enhances microbial biomass C and enzymatic activities [3,43]. Integrated application of manure with inorganic fertilizer provides more methanogenic substrates and thus increases CH_4 emissions [44,45]. In contrast, the lower emissions (7–13%) observed in the UDP treatment compared to PU and IPNS are likely due to increased root growth in subsurface soil, which may improve oxygen availability in the rhizosphere, thus enhancing CH_4 oxidation in subsurface soils and, consequently, reducing CH_4 via methanotrophic bacteria [46,47]. Lower emissions in the UDP treatment could also be associated with retention of N in the reduced zone (anoxic layer) as an NH_4^+ form that can alleviate CH_4 emissions by boosting CH_4 oxidation [46,47]. Since there is no interaction of fertilizer treatment with water regime, season, or year, the effect of UDP and IPNS could be consistent across the range of irrigation regimes and seasons.

Water regime plays a critical role in CH_4 emissions [3,5,25,26]. In this study, AWD significantly ($p < 0.05$) reduced cumulative seasonal CH_4 emissions by 8% in the Aus season (Table 2) and 9% in the Aman season (Table 3) compared to CF conditions. This effect could be more prominent in the dry season, when there is no interruption of the AWD cycle by monsoon rain. These results are in close agreement with previous studies [3,5,13,25,28], such as Islam et al. [3], who observed that AWD irrigation significantly reduced CH_4 emissions by 37% compared to CF conditions in the Boro (dry) season across on-farm and on-station measurements in Bangladesh. Similarly, Win et al. [25] found that AWD irrigation decreased CH_4 emissions by 70% compared to CF conditions in the Boro (dry) season in on-farm measurements in Myanmar. The effect of AWD on reducing CH_4 emissions depends on the intensity of soil drying, soil type, and other cultivation practices [48,49]. Intermittent dry episodes aerate the soil, increase the oxidation of CH_4 by the methanotrophs, and reduce methanogenic activities, thus lowering CH_4 emissions. These results confirm that AWD irrigation has the potential to reduce emissions consistently across the range of management practices.

4.2. N_2O Emissions

N fertilizer and water regime directly affect N_2O emissions. N_2O emission peaks were observed due to the application of fertilizer and irrigation regimes. The IPNS treatment showed higher cumulative N_2O emissions than PU under AWD, but they were similar under CF irrigation. Higher emissions for the IPNS treatments could be associated with the slow and steady release of nutrients from poultry litter, which acts as an additional substrate for nitrification and subsequent denitrification [4,5,11]. However, both the Aus and Aman seasons are mostly rainfed, and AWD irrigation could not be maintained properly (Figure 2) due to frequent rainfall (Figure 1). The relatively small rate of emissions found in the UDP treatment could be associated with slow diffusion of NH_4^+-N in the reduced zone, which decreases the supply of available inorganic N, resulting in reduced nitrification and subsequent denitrification [50,51]. In contrast to UDP, the IPNS treatment resulted in higher emissions in both irrigation regimes due to the combination of PU and poultry litter. The readily accessible N provided by PU also plays an essential role in the early stages of nitrification and denitrification, resulting in substantial emissions of N_2O [52].

AWD irrigation resulted in a significantly ($p < 0.05$) higher level of cumulative N_2O emissions than CF conditions in Aus (Table 2) and Aman (Table 3), which aligns with previous studies [3,5,7]. In general, the level of N_2O emissions is negligible in continuously flooded rice fields due to a lack of frequent nitrification and subsequent denitrification [27,53], while AWD produces substantial N_2O emissions [3,5,7]. The presence of alternate oxic and anoxic conditions, which promotes nitrification and denitrification depending on oxygen availability, was likely to blame for the higher levels of N_2O emissions produced by all treatments when they were subjected to AWD irrigation as compared to CF conditions. On the other hand, denitrification could have been responsible for the decreased emission of N_2O in CF conditions [52,53].

4.3. GWP and GHGI

The IPNS treatment increased GWP by 5% in Aus (Table 2) and 3% in Aman (Table 3) compared to PU due to increased CH_4 emissions, which is supported by previous studies [5,11,42]. However, UDP significantly ($p < 0.05$) decreased GWP and GHGI compared to PU and IPNS in both Aus and Aman seasons (Tables 2 and 3), which agrees with the previous findings [5,9]. Lower GWP and GHGI under the UDP treatment might be correlated with reduced CH_4 emissions and higher rice yields (Tables 2 and 3; Figure 5) [3,5]. Although AWD irrigation significantly ($p < 0.05$) increased cumulative N_2O emissions by 18% in the Aus season and 19% in the Aman season over CF conditions, the increased emissions were mitigated by the reduction in CH_4 emissions. Despite the fact that N_2O has a substantially stronger radiative force than CH_4, the volume of N_2O emissions is quite low. As a result, CH_4 is the primary source of GWP from rice cultivation, accounting for more than 90% of the total [3,5,26,30,31]. In this study, the CH_4-induced GWP was 99.3% and 98.7%, while N_2O-induced GWP was 0.7% and 1.3% in Aus and Aman seasons, respectively. As with GWP, AWD irrigation significantly ($p < 0.05$) reduced GHGI compared to CF irrigation, which is in line with earlier studies [3,5,26,28]. As a result, the most effective interventions for reducing GWP and GHGI in rice production would be UDP and intermittent aeration, both of which have the ability to minimize CH_4 emissions.

5. Conclusions

This study suggests that IPNS has the potential to increase crop productivity and improve soil fertility in the long term. While IPNS may not be effective in mitigating GHG emissions compared to improved N management practices such as UDP, it may not increase emissions compared to the conventional broadcast application of PU. Given that IPNS benefits crop yields and soil fertility, it could be adopted for sustainable improvement of soil fertility and crop productivity. However, further studies should be conducted across soil types, crop management practices, and agroecology with adjustments to the ratio of organic inputs and inorganic fertilizers. AWD irrigation was found to substantially lower GWP and GHGI in both the Aus and Aman seasons compared to CF irrigation. This study confirms that either IPNS or UDP with AWD irrigation could be safely implemented without increasing GHG emissions compared to conventional N management.

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References

1. Mamun, M.A.A.; Nihad, S.A.I.; Sarkar, M.A.R.; Aziz, M.A.; Qayum, M.A.; Ahmed, R.; Rahman, N.M.F.; Hossain, M.I.; Kabir, M.S. Growth and trend analysis of area, production and yield of rice: A scenario of rice security in Bangladesh. *PLoS ONE* **2021**, *16*, e0261128. [CrossRef]
2. IPCC. Climate Change: Synthesis Report. In *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Pachauri, R.K., Meyer, L.A., Eds.; IPCC: Geneva, Switzerland, 2014; p. 151.
3. Islam, S.M.M.; Gaihre, Y.K.; Islam, M.R.; Akter, M.; Mahmud, A.A.; Singh, U.; Sander, B.O. Effects of water management on greenhouse gas emissions from farmers' rice fields in Bangladesh. *Sci. Total Environ.* **2020**, *734*, 139382. [CrossRef] [PubMed]
4. Shakoor, A.; Shakoor, S.; Rehman, A.; Ashraf, F.; Abdullah, M.; Shahzad, S.M.; Farooq, T.H.; Ashraf, M.; Manzoor, M.A.; Altaf, M.M.; et al. Effect of animal manure, crop type, climate zone, and soil attributes on greenhouse gas emissions from agricultural soils—A global meta-analysis. *J. Clean. Prod.* **2021**, *278*, 124019. [CrossRef]
5. Islam, S.M.M.; Gaihre, Y.K.; Islam, M.R.; Ahmed, M.N.; Akter, M.; Singh, U.; Sander, B.O. Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management. *J. Environ. Manag.* **2022**, *307*, 114520. [CrossRef]
6. Dong, N.M.; Brandit, K.K.; Sørensen, J.; Hung, N.N.; Hach, C.V.; Tan, P.S.; Dalsgaard, T. Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Vietnam. *Soil Biol. Biochem.* **2012**, *47*, 166–174. [CrossRef]
7. Islam, S.M.M.; Gaihre, Y.K.; Biswas, J.C.; Jahan, M.S.; Singh, U.; Adhikary, S.K.; Satter, M.A.; Saleque, M.A. 2018. Different nitrogen rates and methods of application for dry season rice cultivation with alternate wetting and drying irrigation: Fate of nitrogen and grain yield. *Agric. Water Manag.* **2018**, *196*, 144–153. [CrossRef]
8. Islam, S.M.M.; Gaihre, Y.K.; Shah, A.L.; Singh, U.; Sarkar, M.I.U.; Satter, M.A.; Sanabria, J.; Biswas, J.C. Rice yields and nitrogen use efficiency with different fertilizers and water management under intensive lowland rice cropping systems in Bangladesh. *Nutr. Cycl. Agroecosyst.* **2016**, *106*, 143–156. [CrossRef]

9. Yao, Z.; Zheng, X.; Zhang, Y.; Liu, C.; Wang, R.; Lin, S.; Zuo, Q.; Butterbach-Bahl, K. Urea deep placement reduces yield-scaled greenhouse gas (CH_4 and N_2O) and NO emissions from a ground cover rice production system. *Sci. Rep.* **2017**, *7*, 11415. [CrossRef]
10. Liu, T.Q.; Li, S.H.; Guo, L.G.; Cao, C.G.; Li, C.F.; Zhai, Z.B.; Zhou, J.Y.; Mei, Y.M.; Ke, H.J. Advantages of nitrogen fertilizer deep placement in greenhouse gas emissions and net ecosystem economic benefits from no-tillage paddy fields. *J. Clean. Prod.* **2020**, *263*, 121322. [CrossRef]
11. Thangarajan, R.; Bolan, N.S.; Tian, G.; Naidu, R.; Kunhikrishnan, A. Role of organic amendment application on greenhouse gas emission from soil. *Sci. Total Environ.* **2013**, *465*, 72–96. [CrossRef]
12. Qaswar, M.; Jing, H.; Ahmed, W.; Dongchu, L.; Shujun, L.; Lu, Z.; Cai, A.; Lisheng, L.; Yongmei, X.; Jusheng, G.; et al. Yield sustainability, soil organic carbon sequestration and nutrients balance under long-term combined application of manure and inorganic fertilizers in acidic paddy soil. *Soil Tillage Res.* **2020**, *198*, 1–6. [CrossRef]
13. Lin, Y.; Watts, D.B.; van Santen, E.; Cao, G. Influence of poultry litter on crop productivity under different field conditions: A meta-analysis. *Agron. J.* **2018**, *110*, 807. [CrossRef]
14. Sarkar, M.I.U.; Jahan, A.; Haque, M.M.; Islam, S.M.M.; Ahmed, M.N.; Islam, M.R. Long term effects of integrated plant nutrition system on rice yield, nitrogen dynamics and biochemical properties in soil of rice–rice cropping system. *Asian J. Soil Sci. Plant Nutr.* **2019**, *4*, 1–14. [CrossRef]
15. Rahman, M.M.; Uddin, S.; Jahangir, M.M.R.; Solaiman, Z.M.; Alamri, S.; Siddiqui, M.H.; Islam, M.R. Integrated nutrient management enhances productivity and nitrogen use efficiency of crops in acidic and charland soils. *Plants* **2021**, *10*, 2547. [CrossRef]
16. Abuarab, M.E.; El-Mogy, M.M.; Hasan, A.M.; Abdeldaym, E.A.; Abdelkader, N.H.; El-Sawy, M.B.I. The effects of root aeration and different soil conditioners on the nutritional values, yield, and water productivity of potato in clay loam soil. *Agronomy* **2019**, *9*, 418. [CrossRef]
17. Gross, C.D.; Bork, E.; Carlyle, C.N.; Chang, S.X. Biochar and its manure-based feedstock have divergent effects on soil organic carbon and greenhouse gas emissions in croplands. *Sci. Total Environ.* **2022**, *806*, 151337. [CrossRef]
18. Araújo, A.; Santos, V.; Monteiro, R. Responses of soil microbial biomass and activity for practices of organic and conventional farming systems in Piauí state, Brazil. *Eur. J. Soil Boil.* **2008**, *44*, 225–230. [CrossRef]
19. Bei, S.; Zhang, Y.L.; Li, T.T.; Christie, P.; Li, X.L.; Zhang, J.L. Response of the soil microbial community to different fertilizer inputs in a wheat-maize rotation on a calcareous soil. *Agric. Ecosyst. Environ.* **2018**, *260*, 58–69. [CrossRef]
20. Zhang, G.; Song, K.; Huang, Q.; Zhu, X.; Gong, H.; Ma, J.; Xu, H. Heavy metal pollution and net greenhouse gas emissions in a rice-wheat rotation system as influenced by partial organic substitution. *J. Environ. Manag.* **2022**, *307*, 114599. [CrossRef]
21. Ravindran, B.; Awasthi, M.K.; Karmegam, N.; Chang, S.W.; Chaudhary, D.K.; Selvam, A.; Nguyen, D.D.; Milon, A.R.; Ramanujam, G.M. Co-composting of food waste and swine manure augmenting biochar and salts: Nutrient dynamics, gaseous emissions and microbial activity. *Bioresour. Technol.* **2022**, *344*, 126300. [CrossRef]
22. Romero, C.M.; Redman, A.A.P.H.; Owens, J.; Terry, S.A.; Ribeiro, G.O.; Gorzelak, M.A.; Oldenburg, T.B.P.; Hazendonk, P.; Larney, F.J.; Hao, X.; et al. Effects of feeding a pine-based biochar to beef cattle on subsequent manure nutrients, organic matter composition and greenhouse gas emissions. *Sci. Total Environ.* **2020**, *812*, 152267. [CrossRef] [PubMed]
23. Das, S.; Adhya, T.K. Effect of combine application of organic manure and inorganic fertilizer on methane and nitrous oxide emissions from a tropical flooded soil planted to rice. *Geoderma* **2014**, *213*, 185–192. [CrossRef]
24. Yadvinder-Singh; Gupta, R.K.; Thind, H.S.; Bijay-Singh; Varinderpal-Singh; Gurpreet-Singh; Jagmohan-Singh; Ladha, J.K. Poultry litter as a nitrogen and phosphorous source for the rice–wheat cropping system. *Biol. Fertil. Soils* **2009**, *45*, 701–710. [CrossRef]
25. Win, E.P.; Win, K.K.; Bellingrath-Kimura, S.D.; Oo, A.Z. Influence of rice varieties, organic manure and water management on greenhouse gas emissions from paddy rice soils. *PLoS ONE* **2021**, *16*, e0253755. [CrossRef] [PubMed]
26. Islam, S.F.; van Groenjgen, J.W.; Jensen, L.S.; Sander, B.O.; de Neergaard, A. The effective mitigation of greenhouse gas emissions from rice paddies without compromising yield by early-season drainage. *Sci. Total Environ.* **2018**, *612*, 1329–1339. [CrossRef]
27. Gaihre, Y.K.; Singh, U.; Islam, S.M.M.; Huda, A.; Islam, M.R.; Sanabria, J.; Satter, M.A.; Islam, M.R.; Biswas, J.C.; Jahiruddin, M.; et al. Nitrous oxide and nitric oxide emissions and nitrogen use efficiency as affected by nitrogen placement in lowland rice fields. *Nutr. Cycl. Agroecosyst.* **2018**, *110*, 277–291. [CrossRef]
28. Ku, H.H.; Hayashi, K.; Agbisit, R.; Villegas-Pangga, G. Evaluation of fertilizer and water management effect on rice performance and greenhouse gas intensity in different seasonal weather of tropical climate. *Sci. Total Environ.* **2017**, *601–602*, 1254–1262. [CrossRef]
29. Islam, S.M.; Gaihre, Y.K.; Biswas, J.C.; Singh, U.; Ahmed, M.N.; Sanabria, J.; Saleque, M.A. Nitrous oxide and nitric oxide emissions from lowland rice cultivation with urea deep placement and alternate wetting and drying irrigation. *Sci. Rep.* **2018**, *8*, 17623. [CrossRef]
30. Sander, B.O.; Samson, M.; Buresh, R.J. Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. *Geoderma* **2014**, *235–236*, 355–362. [CrossRef]
31. Janz, B.; Weller, S.; Kraus, D.; Racela, H.R.; Wassmann, R.; Butterbach-Bahl, K.; Kiese, R. Greenhouse gas footprint of diversifying rice cropping systems: Impacts of water regime and organic amendments. *Agric. Ecosyst. Environ.* **2019**, *270–271*, 41–54. [CrossRef]

32. Liu, L.; Chen, T.; Wang, Z.; Zhang, H.; Yang, J.; Zhang, J. Combination of site-specific nitrogen management and alternate wetting and drying irrigation increases grain yield and nitrogen and water use efficiency in super rice. *Field Crops Res.* **2013**, *154*, 226–235. [CrossRef]
33. Wang, Z.; Zhang, W.; Beebout, S.S.; Liu, L.; Yang, J.; Zhang, J. Grain yield, water and nitrogen use efficiencies of rice as influenced by irrigation regimes and their interaction with nitrogen rates. *Field Crops Res.* **2016**, *193*, 54–69. [CrossRef]
34. Jackson, M.L. *Soil Chemical Analysis*; Constable and Co.: London, UK, 1958.
35. Nelson, D.W.; Sommers, L.E. *Total Carbon, Organic Carbon, and Organic Matter in Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*, 2nd ed.; Page, A.L., Miller, R.H., Keeney, D.R., Eds.; SSSA: Madison, WI, USA, 1982; pp. 539–577.
36. Bremner, J.M. Total Nitrogen. In *Methods of Soil Analysis, Part 2*; Black, C.A., Ed.; American Society of Agronomy: Madison, WI, USA, 1965; pp. 1149–1178.
37. Olsen, S.R.; Sommers, L.E. Phosphorus. In *Methods of Soil Analysis, Part 2*, 2nd ed.; Page, A.L., Miller, R.H., Keeney, D.R., Eds.; Agronomy Monograph 9; ASA and SSSA: Madison, WI, USA, 1982; pp. 403–427.
38. Page, A.L.; Miller, R.H.; Keeney, D.R. (Eds.) *Methods of Soil Analysis Part 2: Chemical and Microbiological Properties*, 2nd ed.; SSSA: Madison, WI, USA, 1982.
39. Bouyoucos, G.J. Hydrometer method improved for making particle size analysis of soils. *Agron. J.* **1962**, *54*, 461–465. [CrossRef]
40. Lampayan, R.M.; Rejesus, R.M.; Singleton, G.R.; Bouman, B.A.M. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crop Res.* **2015**, *170*, 95–108. [CrossRef]
41. Zhan, M.; Cougui, C.; Wang, J.; Jiang, Y.; Cai, M.; Yue, L.; Shahrear, A. Dynamics of methane emission, active soil organic carbon and their relationships in wetland integrated rice–duck systems in southern China. *Nutr. Cycl. Agroecosyst.* **2011**, *89*, 1–13. [CrossRef]
42. Kimani, S.M.; Bimantara, P.O.; Hattori, S.; Tawaraya, K.; Sudo, S.; Xu, X.; Cheng, W. Co-application of poultry-litter biochar with Azolla has synergistic effects on CH_4 and N_2O emissions from rice paddy soils. *Heliyon* **2020**, *6*, e05042. [CrossRef]
43. Liu, M.; Hu, F.; Chen, X.; Huang, Q.; Jiao, J.; Zhang, B.; Li, H. Organic amendments with reduced chemical fertilizer promote soil microbial development and nutrient availability in a subtropical paddy field: The influence of quantity, type and application time of organic amendments. *Appl. Soil Ecol.* **2009**, *42*, 166–175. [CrossRef]
44. Das, S.; Bhattacharyya, P.; Adhya, T.K. Interaction effect of elevated CO_2 and temperature on microbial biomass and enzyme activities in tropical rice soils. *Environ. Monit. Assess.* **2011**, *182*, 555–569. [CrossRef]
45. Pathak, H. Review: Common attributes of hydraulically fractured oil and gas production and CO_2 geological sequestration. *Greenh. Gases Sci. Technol.* **2015**, *2*, 352e368. [CrossRef]
46. Gilbert, B.; Frenzel, P. Rice roots and CH_4 oxidation: The activity of bacteria, their distribution and the microenvironment. *Soil Biol. Biochem.* **1998**, *30*, 1903–1916. [CrossRef]
47. Bodelier, P.L.; Roslev, P.; Henckel, T.; Frenzel, P. Stimulation by ammonium based fertilizers of methane oxidation in soil around rice roots. *Nature* **2000**, *43*, 421–424. [CrossRef] [PubMed]
48. Liang, K.; Zhong, X.; Huang, N.; Lampayan, R.M.; Pan, J.; Tian, K.; Liu, Y. Grain yield, water productivity and CH_4 emission of irrigated rice in response to water management in south China. *Agric. Water Manag.* **2016**, *163*, 319–331. [CrossRef]
49. Xu, Y.; Ge, J.; Tian, S.; Li, S.; Nguy-Robertson, A.L.; Zhan, M.; Cao, C. Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. *Sci. Total Environ.* **2015**, *505*, 1043–1052. [CrossRef]
50. Kapoor, V.; Singh, U.; Patil, S.K.; Magre, H.; Shrivastava, L.K.; Mishra, V.N.; Das, R.O.; Samadhiya, V.K.; Sanabria, J.; Diamond, R. Rice growth, grain yield, and floodwater nutrient dynamics as affected by nutrient placement method and rate. *Agron. J.* **2008**, *100*, 526–536. [CrossRef]
51. Rochette, P.; Angers, D.A.; Chantigny, M.H.; Gasser, M.O.; MacDonald, J.D.; Pelster, D.E.; Bertrand, N. Ammonia volatilization and nitrogen retention: How deep to incorporate urea? *J. Environ. Qual.* **2013**, *42*, 1635–1642. [CrossRef]
52. Firestone, M.K.; Davidson, E.A. Microbiological basis of NO and N_2O production and consumption in soil. In *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere*; Andreae, M.O., Schimel, D.S., Eds.; John Wiley and Sons: Chichester, UK, 1989; pp. 7–21.
53. Zou, J.W.; Huang, Y.; Jiang, J.Y.; Zheng, X.H.; Sass, R.L. A 3-Year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. *Glob. Biogeochem. Cycles* **2005**, *19*, GB2021. [CrossRef]