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Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management

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ABSTRACT

Greenhouse gas (GHG) emissions from agriculture sector play an important role for global warming and climate change. Thus, it is necessary to find out GHG emissions mitigation strategies from rice cultivation. The efficient management of nitrogen fertilizer using urea deep placement (UDP) and the use of the water-saving alternate wetting and drying (AWD) irrigation could mitigate greenhouse gas (GHG) emissions and reduce environmental pollution. However, there is a dearth of studies on the impacts of UDP and the integrated plant nutrient system (IPNS) which combines poultry manure and prilled urea (PU) with different irrigation regimes on GHG emissions, nitrogen use efficiency (NUE) and rice yields. We conducted field experiments during the dry seasons of 2018, 2019, and 2020 to compare the effects of four fertilizer treatments including control (no N), PU, UDP, and IPNS in combination with two irrigation systems— (AWD and continuous flooding, CF) on GHG emissions, NUE and rice yield. Fertilizer treatments had significant ($p < 0.05$) interaction effects with irrigation regimes on methane (CH_4) and nitrous oxide (N_2O) emissions. PU reduced CH_4 and N_2O emissions by 6% and 20% compared to IPNS treatment, respectively under AWD irrigation, but produced similar emissions under CF irrigation. Similarly, UDP reduced cumulative CH_4 emissions by 9% and 15% under AWD irrigation, and 9% and 11% under CF condition compared to PU and IPNS treatments, respectively. Across the year and fertilizer treatments, AWD irrigation significantly ($p < 0.05$) reduced cumulative CH_4 emissions and GHG intensity by 28%, and 26%, respectively without significant yield loss compared to CF condition. Although AWD irrigation increased cumulative N_2O emissions by 73%, it reduced the total global warming potential by 27% compared to CF irrigation. The CH_4 emission factor for AWD was lower (1.67 kg ha^{-1} day^{-1}) compared to CF (2.33 kg ha^{-1} day^{-1}). Across the irrigation regimes, UDP increased rice yield by 21% and N recovery efficiency by 58% compared to PU. These results suggest that both UDP and AWD irrigation might be considered as a carbon-friendly technology.

1. Introduction

Like for more than half of the world's population, rice is the major food for the 160 million people in Bangladesh. In the country, rice is cultivated in two to three seasons in a year and occupies about 11.4 million ha of land, with a production of 36.6 million tons during the year 2019–20 (BBS, 2020). Among the three rice-growing seasons, dry season rice (here after called Boro rice) makes up the majority of the total production (19.6 million tons), covering 4.8 million ha (BBS, 2020). With the increasing population growth rate, it is projected that the demand for rice by 2050 will be 56% higher compared to the 25.1 million tons production level in 2001 (Mukherjee et al., 2011; Kabir et al., 2015). To meet this demand, rice productivity needs to be increased. One way to do so is by adopting improved agricultural practices including the efficient management of fertilizers and irrigation.

Rice cultivation alone contributes about 30% of the total global agricultural CH_4 emissions (IPCC, 2007) and the magnitude of emission depend on crop management practices. Improved crop management

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practices such as efficient fertilizer and water management, appropriate use of crop residues could help to mitigate GHG emissions (Romasanta et al., 2017; Islam et al., 2020). Improved placement of nitrogen fertilizer such as urea deep placement (UDP), and improved irrigation water management such as alternate wetting and drying (AWD) are known to mitigate GHG emissions from rice fields (Islam et al., 2020; Shakoor et al., 2021).

N fertilizers play a critical role in increasing rice productivity. However, current N fertilizers (mostly urea) management practice in Bangladesh is not efficient as most farmers apply fertilizer through broadcasting method. On the average, N fertilizer application rate is 120–130 kg N ha^{-1} (BRRI, 2020) for short duration rice varieties (growth duration: $<$ 150 days). As more than 50% of applied N fertilizer is lost from soil-plant systems to the environment, broadcasting contributes to pollution of air and groundwater due to increased N losses through ammonia (NH_3) volatilization, surface runoff, nitrification and denitrification, and leaching and lower nitrogen use efficiency (NUE) (Dong et al., 2012; Islam et al., 2018c). Moreover, inefficient N application could increase CH_4 emissions (Banger et al., 2012; Linquist et al., 2012). Annually, Bangladesh consumes about 2.9 million metric ton of urea in about 60% of this is used in rice cultivation (BBS, 2020). Therefore, this could contribute to increase atmospheric pollution due to increased CH_4 and N_2O emissions. Previous literature reported that changing N application from surface broadcasting to sub-surface (or root-zone) application, commonly called UDP, substantially reduces N losses, and GHG emissions (Islam et al., 2016, 2018c; Yao et al., 2017; Liu et al., 2020). UDP could reduce CH_4 emissions due to increase O_2 availability in the rhizosphere that enhance CH_4 consumption but increase N_2O emissions due to increases in microbial nitrification of NH_4^+ and subsequent denitrification of NO_3^- (Linquist et al., 2012). In contrast, Chatterjee et al. (2018) reported that urea deep placement (UDP) could mitigate N_2O emissions since it retains N in soils as non-exchangeable ammonium (NH_4^+) for a longer time. This helps to supply N throughout the rice-growing season and a negligible amount of NH_4^+-N diffuses from reduced zone to the soil surface or floodwater. However, it could promote CH_4 emissions through the enhanced CH_4 transport pathway from the soil to atmosphere due to improved root and shoot growth of rice and providing more carbon substrate for methanogenesis. The contradiction among these results may arise from the variations in the source and amount of N fertilizer, soil, climate conditions, and their interactions (Linquist et al., 2012; Adviento-Borbe and Linquist, 2016). It is not clear whether UDP in rice cultivation mitigates or increases the total GHG emissions (CH_4 and N_2O) across different water regimes. Therefore, further research is needed to identify the effect of UDP on GHG emissions from the rice field, particularly with AWD irrigation across the country in order to understand the environmental benefits of UDP by raising awareness of farmers and policy makers on importance of water saving irrigation on protecting environment.

Water saving irrigation AWD is becoming popular as it could be effective in mitigating total GHG emissions from irrigated rice fields (Islam et al., 2020; Win et al., 2021). Moreover, AWD irrigation getting popular due to increasing scarcity of irrigation water. In Bangladesh, it is reported that groundwater table is declining due to continuous extraction for irrigating for Boro (dry season) rice. AWD irrigation saves water by up to 38% without significant yield loss (Lampayan et al., 2015). Although AWD irrigation increases N_2O emission due to increased nitrification during drying period and denitrification during wetting period. In contrast, under continuous flooding, N is retained in the form of ammonium, thus there is less availability of nitrate N for the denitrification. However, the increased N_2O emissions could be offset by reduced CH_4 emissions as N_2O emissions contribute $\leq$5% to the total GWP in rice cultivation (Sander et al., 2014; Islam et al., 2018b; Islam et al., 2020). Therefore, both UDP and AWD irrigation are considered climate-smart technologies in rice cultivation as they are effective in reducing GHG emissions and increasing farm profits.

Similarly, the incorporation of organic inputs increases organic carbon (OC) reserves in the soil, thereby improving soil fertility and crop productivity (Yadvinder-Singh et al., 2009; Lin et al., 2018; Sarkar et al., 2019) and also affecting GHG emissions (Thangarajan et al., 2013; Das and Adhya, 2014; Shakoor et al., 2021). As organic inputs contain lower levels of nutrients compared to inorganic fertilizer, they are often applied in combination with inorganic fertilizers, with the ratio depending on the availability of organic inputs. The model of combined application is called integrated plant nutrient system (IPNS). One of the locally available organic inputs, which is widely used in Bangladesh, is poultry manure. This provides readily available carbon (C) and N to the soil that act as additional substrate for methanogens and nitrifying-denitrifying bacteria, resulting in higher amounts of CH_4 and N_2O emissions (Das and Adhya, 2014; Shakoor et al., 2021). In IPNS, the supply of C and N is sustained for a longer period due to slow mineralization, thus improving crop growth through effective tillers and increasing rice yields (Yadvinder-Singh et al., 2009; Lin et al., 2018; Sarkar et al., 2019). However, the effects of integrated plant nutrient system (IPNS), particularly the combined application of prilled urea and poultry manure on GHG emissions are not well documented. More research is thus needed to investigate the impacts of IPNS on rice yields and emissions under different irrigation regimes. This type of studies helps to increase understanding on the environmental benefits of fertilizer treatments in combination with water regimes so that public awareness and decision making by policy makers about carbon-friendly farming could be increased.

This current study investigated the effects of urea deep placement (UDP) and integrated plant nutrient system (IPNS) treatment as well as their interaction with irrigation regimes such as AWD and continuous flooding (CF) on GHG emissions, rice yield, and nitrogen use efficiency (NUE). It is hypothesized that UDP with AWD irrigation could mitigate GHG emissions compared to broadcast prilled urea and IPNS treatment with CF irrigation. To test this hypothesis, multi-year field experiments were conducted in Bangladesh to determine the impacts of UDP and IPNS amendment across different irrigation regimes on GHG emissions, rice yield, and NUE.

2. Materials and methods

2.1. Experimental site and weather conditions

The field experiments were conducted during three consecutive Boro season in 2018, 2019, and 2020 at the Bangladesh Rice Research Institute (BRRI) farm in Gazipur, Bangladesh (latitude: 23°59'25" N, longitude: 90°24'33" E). The dominant cropping pattern in the region is dry season rice (Boro rice)-fallow-wet season rice (Aman rice; June/July–November/December). Boro rice is cultivated during the dry season (December/January to March/April) and irrigation is mostly done through groundwater extraction, while Aman rice is mostly rainfed. The air temperature during this season generally ranges from 15 to 30 °C. The average annual rainfall is ca. 2000 mm, which mostly occurs during the monsoon season (June–August). Fig. 1 presents the daily average air temperature, rainfall, and solar radiation during the experimental period. The soil in the experimental site is slightly acidic, low in OC, and poor in potassium (K). Details of the physicochemical properties of the soil before the start of the experiments are shown in Table 1.

2.2. Experimental design and treatments

A field experiment was conducted in a split-plot design with three replications. Irrigation regimes were considered as main plots and fertilizer treatments were as sub-plots. The four fertilizer treatments were different N sources, namely (i) control: 0 kg N ha^{-1}; (ii) urea deep placement (UDP) at 78 kg N ha^{-1}; (iii) prilled urea (PU) broadcast application at 78 kg N ha^{-1}; and (iv) poultry manure in combination with PU (integrated plant nutrient system, IPNS) at 78 kg N ha^{-1}. Each treatment was tested under two irrigation regimes i.e., alternate wetting

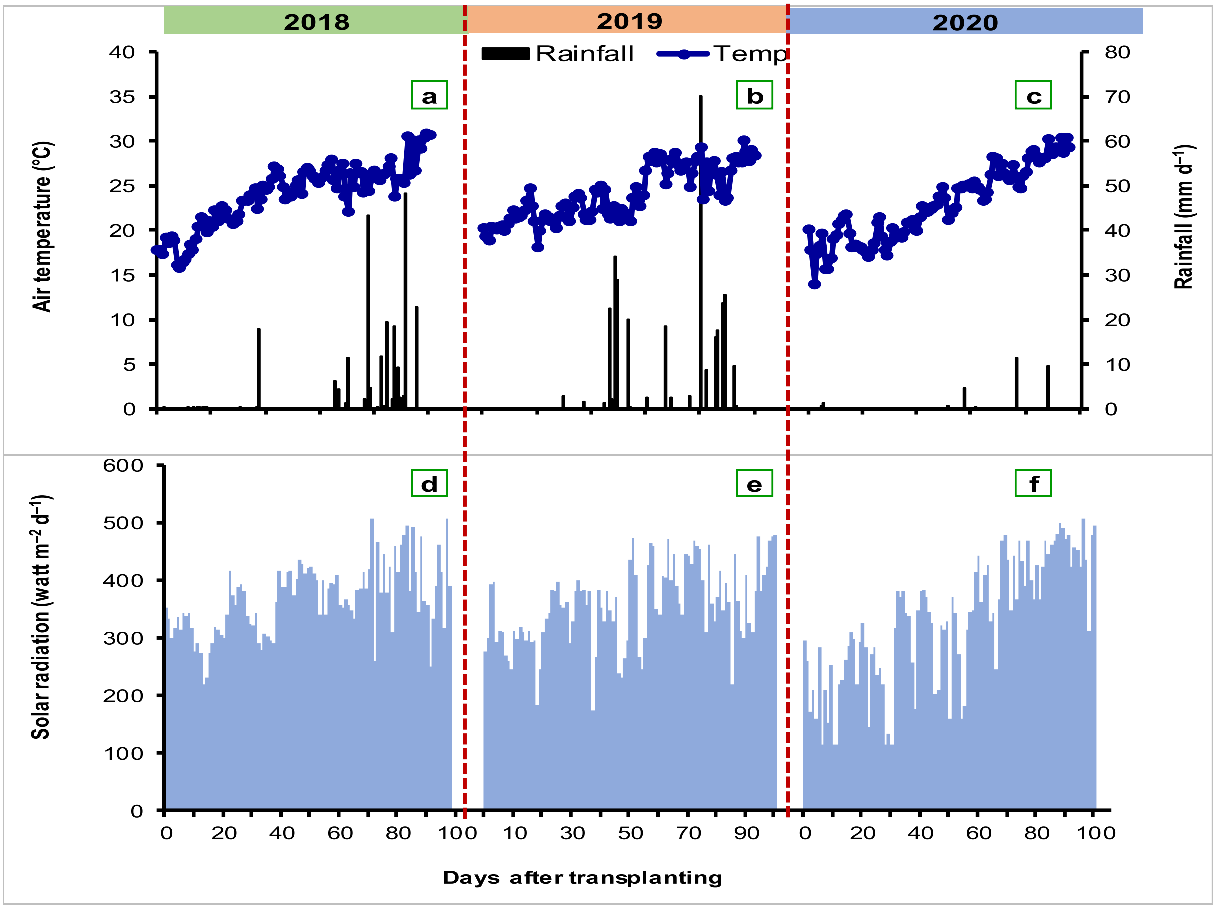

Fig. 1. Daily average rainfall, air temperature and solar radiation during the experimental period in the Boro season of 2018, 2019, and 2020. (Data source: Weather station, Bangladesh Rice Research Institute, Gazipur).

Table 1
Physicochemical properties of the soil before the start of the experiments.

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

and drying (AWD) and continuous flooding (CF). AWD irrigation is effective only during the Boro season as monsoon rain may interrupt AWD cycle during Aman season (wet season). Therefore, this report presents results of only Boro rice.

For UDP, prilled urea was compressed physically and made briquette using briquette machine (Savant and Stangel, 1990) for ease of deep placement. Each briquette size was 2.7 g and was deeply placed into the soils at 8–10 cm depth manually at 40 × 40 cm spacing (62,500 placement sites per ha). With this method of application, each briquette provides N to four hills of rice. The briquettes were deeply placed as a single application after 8–10 days after transplanting (DAT), when puddled soil has settled. Each experimental plot (4.8 m × 3.2 m) was separated by a 40 cm wide levee.

2.3. *Crop management*

Each experimental plot was puddled and prepared for transplanting following protocol suggested by Bangladesh Rice Research Institute (BRRI). Rice (Cultivar, BRRI dhan28) seedlings were transplanted at 20 × 20 cm distance. After the harvest of Aman rice, mustard crop was grown before the Boro season rice in 2018 and crop residues of mustard crop (preceding crop) were incorporated in each plot one week before rice transplanting. All agronomic practices such as fertilizer management, irrigation, plant protection measures were done following government recommendations. Details of crop management practices are shown in Table 2. Phosphorus (P), potassium (K), sulfur (S), and zinc (Zn) fertilizers were applied at 25 kg, 85 kg, 15 kg, and 3 kg ha^{-1}, respectively.

For the IPNS treatment, 50% N (39 kg) was supplied from prilled urea (PU) and the remaining 50% (39 kg) from poultry manure. Well

Table 2
Dates of crop management practices.

	Boro 2018	Boro 2019	Boro 2020
Basal fertilization	24-01-2018	10-01-2019	18-01-2020
Variety	BRRI dhan28	BRRI dhan28	BRRI dhan28
Growth duration (day)	135–140	135–140	135–140
Seedling age (day)	40	41	40
Transplanting	25-01-2018	11-01-2019	19-01-2018
First topdressing	01-02-2018	19-01-2019	28-01-2018
Second topdressing	01-03-2018	13-02-2019	16-02-2018
Third topdressing	20-03-2018	02-03-2019	04-03-2018
Harvest	30-04-2018	15-04-2019	24-04-2018

decomposed (air dry) poultry manure (C: N of 11.5:1, 13.9% OC, 1.21% N, 0.72% P, and 0.91% K) at 8.5 kg per plot was incorporated into the soil during final land preparation. PU was applied by broadcasting method at three equal splits at 7–10 days after transplanting (DAT), maximum tillering and panicle initiation stages.

For irrigation, plots under the continuous flooding (CF) condition were irrigated regularly until 14 days before harvesting of the crop (Fig. 2d–f). AWD plots were irrigated when floodwater depth dropped to 12–15 cm below soil surface (Fig. 2a–c). For monitoring of floodwater depth, a perforated PVC pipe was inserted (15 cm depth) in each AWD plot. However, all experimental plots were maintained continuously flooded for a week after topdressing of PU and during the flowering stage.

2.4. Gas sampling

Gas samples of CH_4 and N_2O were collected using the closed chamber technique and laboratory analysis was conducted using gas chromatography as explained by Islam et al. (2020). In brief, each closed chamber had a base (70 L) and a cover (chamber-top; 216 L). The chamber-base was installed in the experimental plot one day before the first gas sampling day. The base was inserted at 8–10 cm soil depth to avoid gas exchange between the inside and outside of the chamber. During gas sampling time, the chamber was closed airtight, keeping the chamber-top over the chamber-base. Gas sampling was done once a week at 9:00 a.m. Gas samples were collected using a 50 mL airtight syringe with three-way stop cock at 15-min intervals (0, 15, and 30 min). Collected gas samples were immediately transferred into 30-mL air-evacuated glass vials sealed with a butyl rubber septum for laboratory analysis.

2.5. Estimation of CH_4 and N_2O emissions

The mixing ratio of CH_4 and N_2O in the collected samples was determined by gas chromatography system and emission rates were calculated from the slope of the linear regression curves of CH_4 and N_2O concentration against chamber closer time using the following equation (Islam et al., 2020).

$$\mathrm{CH_4 and\ N_2O\ emissions\ rate}\ \left(\mathrm{mg\ m^{-1}d^{-1}}\right) = \frac{Slope\ (ppm\ min^{-1})\ \times\ Vc\ \times\ MW\ \times\ 60\ \times\ 24}{22.4\ \times\ \{(273+\ T)/273\}\ \times\ Ac\ \times\ 1000}$$

where, Vc is the volume of the gas chamber in liters (L), MW is the molecular weight of the respective gas, 60 is min h^{-1}, 24 is h d^{-1}, 22.4 is the volume of 1 mol of gas in L at standard temperature and pressure, 273 is the standard temperature in °K, T is the temperature inside the chamber in °C, Ac is the area of the chamber in m^2, and 1000 is μg mg^{-1}.

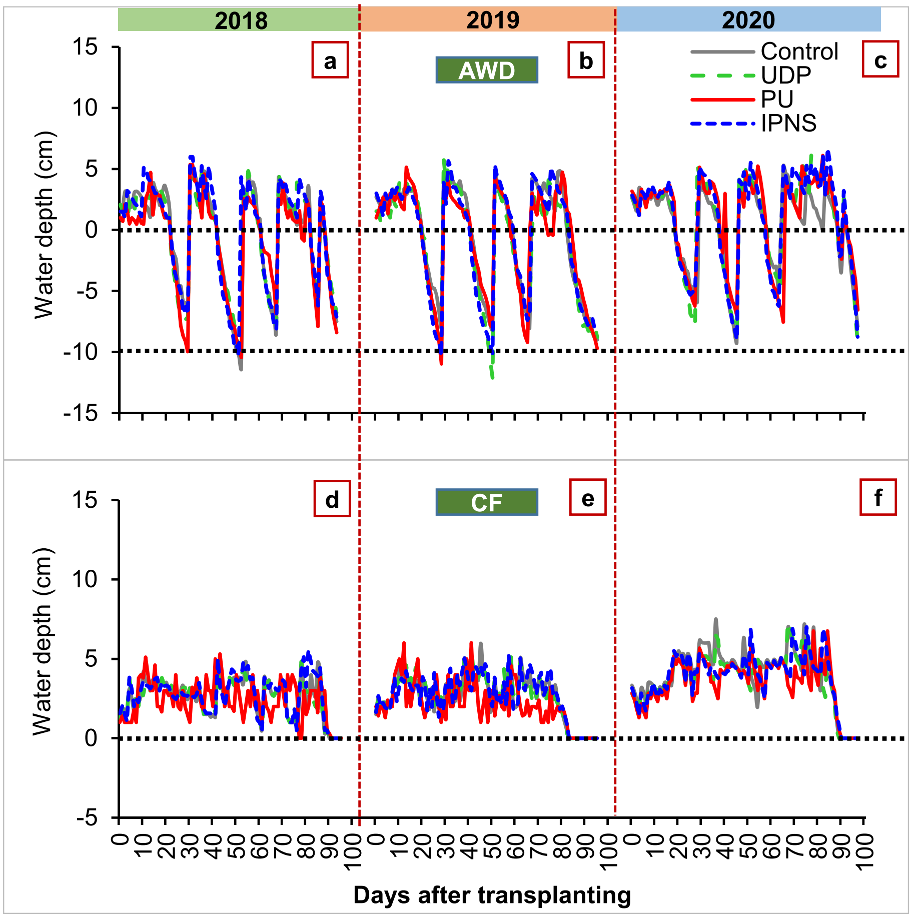

Fig. 2. Daily field water depth from transplanting to harvesting of rice plant in the Boro season under AWD and CF condition. UDP, PU, and IPNS denote urea deep placement, prilled urea, and integrated plant nutrient system, respectively.

Cumulative CH_4 and N_2O emissions were estimated by summing up the daily emissions. Emission rates between two sampling days were estimated by linear interpolation of two consecutive measurements.

$$\text{Emission factor(EF)of } N_2O(\%) = \left[N_2O_{(tr)} - N_2O_{(cr)}\right] * 100 / \text{N rate}_{(tr)}$$

where, $N_2O_{(tr)}$ is the cumulative N_2O emission (g N ha^{-1}) from treatment t and replication r, $N_2O_{(cr)}$ is the cumulative N_2O emission (g N ha^{-1}) from control and replication r, and N $\text{rate}_{(tr)}$ is the N applied (g N ha^{-1}) to treatment t and replication r.

The direct GWP of CH_4 and N_2O was calculated using the following equation:

$$\text{GWP}\left(\text{kg } CO_2 \text{ equivalent } ha^{-1}\right) = \left(TCH_4 \times 28 + TN_2O \times 265\right)$$

where, TCH_4 is the total amount of CH_4 emission (kg ha^{-1}), TN_2O is the total amount of N_2O emission (kg ha^{-1}), 28 and 265 are the GWP values for CH_4 and N_2O, respectively, to CO_2 over a 100-year time horizon (IPCC, 2014). This study has not estimated the indirect GWP associated with C sequestration and other indirect emissions such as use of fuel and electricity, labor etc.

Greenhouse gas emission intensity (GHGI) or yield-scaled emission was calculated by dividing the total GHG emissions by grain yields (kg CO_2 eq kg^{-1} grain yield).

Scaling factor (used to adjust the baseline emissions) for AWD was estimated dividing a cumulative emission from AWD by a cumulative emission from CF.

2.6. *Rice yield and NUE*

For recording grain and straw yield, rice plants from a 5 m^2 area were harvested. The grain yield was calculated at 14% moisture content. The N content of grain and straw was determined by micro Kjeldahl method (Yoshida et al., 1976). The total N uptake (TNU) by grain and straw was estimated. The nitrogen use efficiency (NUE) including agronomic efficiency (AE_N; kg grain kg^{-1} N applied) and recovery efficiency (RE_N; kg N uptake per kg^{-1} N applied) were calculated for all treatments.

2.7. *Data analysis*

Analysis of variance (ANOVA) of the GHG emissions, global warming potential (GWP), greenhouse gas intensity (GHGI), rice yield, and NUE was conducted with the Statistical Tool for Agricultural Research (STAR

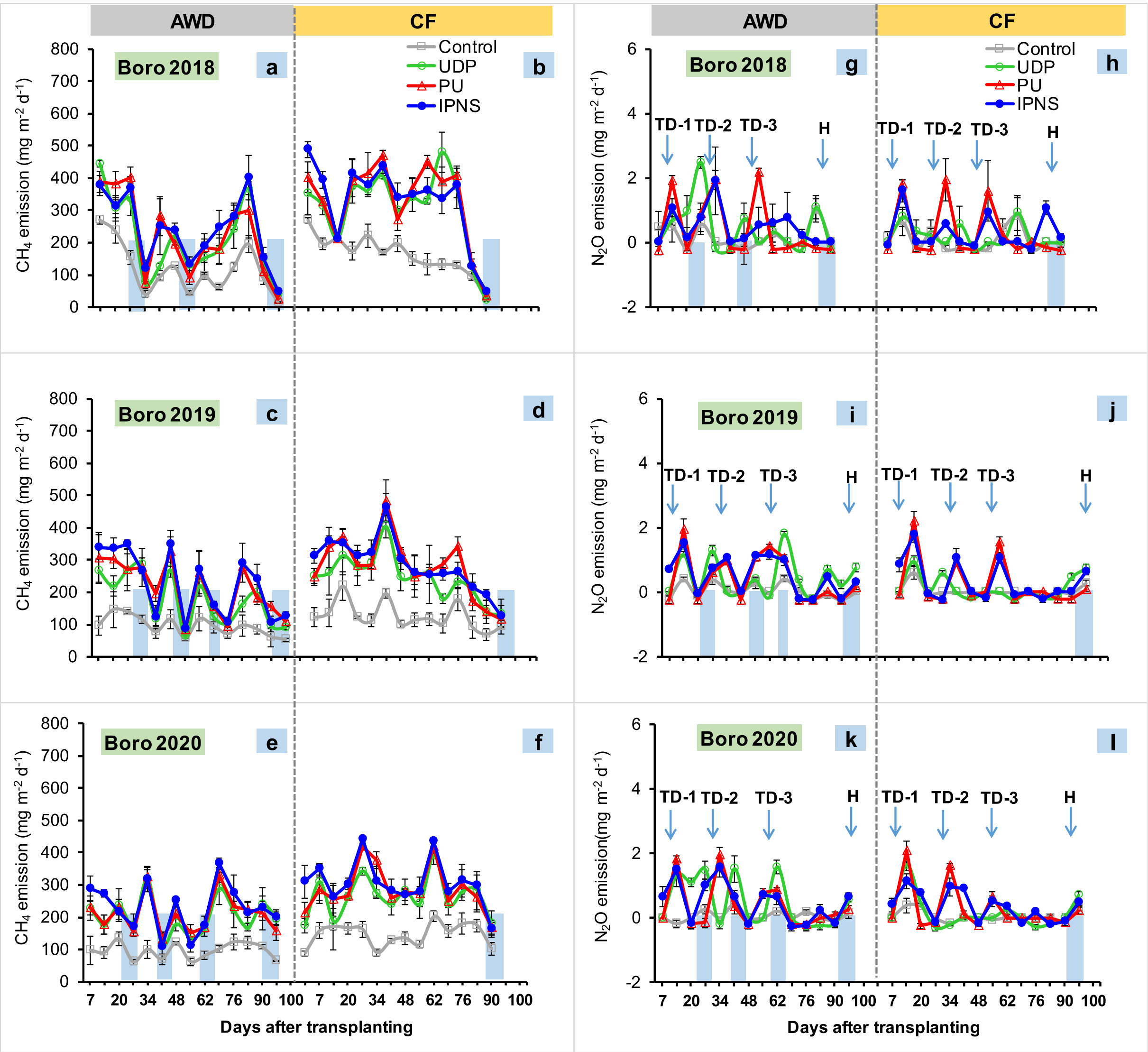

Fig. 3. Temporal dynamics of CH_4 and N_2O emission rates under AWD and CF irrigation regimes during the Boro season of 2018, 2019, and 2020 at BRRI farm, Gazipur. T, TD-1, TD-2, TD-3, H, UDP, PU and IPNS denote transplanting, first topdressing, second topdressing, third topdressing, harvesting, urea deep placement, prilled urea, and integrated plant nutrient system, respectively. Shaded area indicates the drying period under AWD and CF irrigation.

2.0.1, International Rice Research Institute, Philippines) software. ANOVA was performed with a split-plot structure considering the irrigation regimes as the main plot and fertilizer treatments as the sub-plot. Post-hoc analysis mean grouping was done with Tukey's honest significant difference test at a 5% level of probability.

3. Results

3.1. CH_4 emissions

The magnitudes of CH_4 emissions were differed with fertilizer treatments, irrigation regimes, and year (Fig. 3). Two to three emission peaks were observed throughout the crop growth period. CH_4 emission rates were initially low (except in 2018) but they increased with crop growth under both irrigation regimes. The magnitudes of emission peaks were greater in prilled urea (PU) and integrated plant nutrient system (IPNS) treatments compared to the urea deep placement (UDP) treatment. CH_4 emission rates from all fertilizer treatments declined rapidly during dry periods. Generally, the magnitudes of CH_4 emission rates were higher in continuous flooding (CF) condition than in the alternate wetting and drying (AWD) irrigation regime. The daily CH_4 emissions ranged from 16 to 445 mg $m^{-2}d^{-1}$ under AWD irrigation and from 69 to 488 mg $m^{-2}d^{-1}$ under CF condition.

The fertilizer treatments had significant ($p < 0.05$) interaction effects on cumulative CH_4 emissions and emission factor (EF) (Table 3). Control treatment produced the lowest CH_4 emissions, while application of N fertilizer significantly ($p < 0.05$) increased cumulative CH_4 emissions (Table 3). Across water regimes, UDP significantly ($p < 0.05$) reduced cumulative CH_4 emissions and EF compared to broadcast PU and IPNS treatments. In AWD irrigation, the PU treatment showed lower emissions and, thus, resulted in lower EFs than the IPNS treatment. Under CF condition, both PU and IPNS treatments produced similar emissions and EFs. Across the year and fertilizer treatments, AWD irrigation reduced emissions by 28% over CF irrigation. Across the fertilizer treatments, EFs of CH_4 ranged from 0.92 to 2.07 kg ha^{-1} day^{-1} under AWD irrigation, while they ranged from 1.31 to 2.78 kg ha^{-1} day^{-1} under CF condition (Table 3). Across the year and fertilizer treatments, EFs of CH_4 were 1.67 and 2.33 kg ha^{-1} day^{-1} under AWD and CF conditions, respectively. Similarly, across the treatments, the AWD scaling factors (SF) for CH_4 varied from 0.70 to 0.74.

3.2. N_2O emissions

N_2O emission rates varied with application of N fertilizer and irrigation regime (Fig. 3). In AWD irrigation, emission peaks were observed during the dry period in addition to fertilizer application, while in continuous flooding (CF) condition, emission peaks occurred only after fertilizer application. However, some emissions peaks might have been missed as measurements were done at weekly interval. For the rest of the time during the rice growing season, emission rates in the fertilized treatments were similar with those in the control treatment. During dry periods, N_2O emission peaks were more prominent in the urea deep placement (UDP) compared to the prilled urea (PU) and integrated plant nutrient system (IPNS) treatments (Fig. 3g-l). In contrast, peaks in N_2O emissions were greater in the PU treatment compared to UDP and IPNS treatments under CF irrigation. Generally, the magnitudes of N_2O emission peaks were more prominent in AWD irrigation compared to CF condition. Some emission peaks were also found after final drainage for harvest of the rice. On the average, N_2O emissions ranged from −0.24 to 2.49 mg N m^{-2} d^{-1} under AWD irrigation, and from −0.25 to 2.11 mg N m^{-2} d^{-1} under CF condition.

Cumulative N_2O emissions were affected by both fertilizer and water regimes (Table 3). Broadcast PU significantly ($p < 0.05$) reduced cumulative emissions and EF compared to the UDP and IPNS treatments

Table 3
The effects of fertilizer × water regimes and year × water regimes on seasonal CH_4 and N_2O emissions, and emission factor of CH_4 and N_2O, GWP, and GHGI in the Boro season.

Year	Fertilizer management	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 (% N, w/w)		GWP[b]		GHGI[c]	
		AWD	CF	AWD	CF	AWD	CF	AWD	CF	AWD	CF	Mean of 2 water regimes	
Fertilizer and water regimes interaction													
Mean	Control-N0	92.0d	131.3c	0.92d	1.31c	94.3c	56.2c	–	–	2613.8d	3699.2c	1.14c	
	UDP-N78	176.0c	248.4b	1.76c	2.48b	424.6a	141.4b	0.43a	0.11b	5105.5c	7012.6b	1.03d	
	PU-N78	193.7b	272.9a	1.94b	2.73a	361.9b	275.4a	0.34b	0.28a	5573.4b	7756.6a	1.37a	
	IPNS-N78	207.1a	278.4a	2.07a	2.78a	454.4a	297.8a	0.46a	0.31a	5989.0a	7919.6a	1.25b	
Year and water regimes interaction	AWD	CF	AWD	CF	Mean of 2 water regimes	AWD	CF	AWD	CF	AWD	CF		
2018	Mean	164.4a	240.2a	1.65a	2.40a	269.82 ab	0.31b	0.20b	4744.9a	6808.8a	1.04a	1.39b	
2019		164.1a	219.0b	1.64a	2.19b	243.86b	0.44a	0.21b	4728.0a	6201.1b	0.98b	1.29c	
2020		173.1a	239.1a	1.73a	2.39a	276.11a	0.48a	0.29a	4988.6a	6781.1a	1.03 ab	1.46a	
Effects of water regimes													
Mean	Mean	167.2B	232.7A	1.67B	2.33A	333.8A	192.7B	0.41A	0.23B	4820.4B	6597.0A	1.02B	1.38A
ANOVA (p values)													
Water regimes (W)		0.0000		0.0000		0.0000		0.0000		0.0000		0.0000	
Fertilizer (F)		0.0000		0.0000		0.0000		0.0000		0.0000		0.0000	
Year (Y)		0.0837		0.0847		0.1834		0.0011		0.0763		0.1450	
W × F		0.0001		0.0001		0.0000		0.0000		0.0001		0.3654	
W × Y		0.0399		0.0347		0.7873		0.0137		0.0377		0.0391	
F × Y		0.2581		0.2586		0.0049		0.2293		0.2277		0.7626	
W × F × Y		0.4713		0.4699		0.1183		0.2680		0.4086		0.4255	

Within a column, means followed by same lowercase letters and within a row for each response variable, means followed by the same uppercase letters are not significantly different at 5% level of probability by Tukeys's honest significant difference (HSD) test. UDP, PU, and IPNS indicate urea deep placement, prilled urea, and integrated plant nutrient system, respectively.

[a] EF of CH_4 (kg ha^{-1} d^{-1}) was calculated by dividing total CH_4 emissions (kg ha^{-1}) by active rice growth period (days).

[b] GWP (global warming potential; 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 (IPCC 2014).

[c] GHGI (greenhouse gas intensity; kg CO_2 equivalent kg^{-1} grain yield) was calculated by dividing total GWP by grain yield (kg ha^{-1}).

under AWD irrigation. Under CF condition, UDP significantly ($p < 0.05$) reduced N_2O emissions and EFs compared to the PU and IPNS treatments (Table 3). AWD irrigation increased seasonal total N_2O emission by 73% over conventional irrigation practice of continuous flooding.

3.3. GWP and GHGI

There was a significant ($p < 0.05$) interaction effect of fertilizer treatments and water regimes on global warming potential (GWP) (Table 3). Compared to the prilled urea (PU) and integrated plant nutrient system (IPNS) treatments, urea deep placement (UDP) reduced GWP by 8% and 15%, respectively, under AWD irrigation and by 10% and 11%, respectively, under CF irrigation. The PU treatment had lower GWP compared to the IPNS treatment under AWD irrigation. However, no significant variation in GWP was observed between PU and IPNS treatments under CF irrigation (Table 3). The control treatment produced the lowest GWP in both irrigation regimes. On the average, AWD irrigation lowered GWP by 27% over CF irrigation. UDP reduced greenhouse gas intensity (GHGI) compared to the PU and IPNS treatments (Table 3). In contrast, the PU treatment had higher GHGI than the IPNS treatment. As in GWP, AWD irrigation reduced GHGI by 26% compared to CF irrigation (Table 3).

3.4. Rice yield, nitrogen uptake, and NUE

Across the water regimes and years, the UDP and IPNS treatments significantly ($p < 0.05$) increased rice yield compared to PU (Table 4). Rice yields between the UDP and IPNS treatments were similar. Water regimes had no significant effects on rice yield. UDP had greater total nitrogen uptake (TNU), agronomic efficiency (AE_N), and recovery efficiency (RE_N) followed by the IPNS and PU treatments (Table 4). Water regimes had no significant effects on rice yields, TNU, AE_N, and RE_N.

4. Discussion

4.1. CH_4 emissions

Methane emissions from rice fields are directly or indirectly affected by the application of C and N. Addition of C substrate such organic inputs in soils increases emissions. Higher emission rates as observed in 2018 compared to 2019 and 2020 could be due to the incorporation of mustard biomass, which could have provided additional C substrate for methanogenesis, thus the increased CH_4 production. The IPNS treatment showed greater CH_4 emissions compared to broadcast PU (Table 3), probably due to an increased C supply owing to the application of poultry manure which might have enhanced microbial activities and decreased soil redox potential (Lee et al., 2010). Increased emissions from the application of organic inputs were also reported by previous studies (Thangarajan et al., 2013; Kimani et al., 2020). In contrast, urea deep placement (UDP) reduced cumulative CH_4 emissions compared to the integrated plant nutrient system (IPNS) treatment (Table 3). This could be due to increased oxygen availability in the rhizosphere as UDP improves root growth, thus, enhancing CH_4 oxidation by methanotrophic bacteria in subsurface soils and consequently reducing the CH_4 emission (Gilbert and Frenzel, 1998; Bodelier et al., 2000). UDP enhanced the growth of the rice plants, increased the labile soil organic carbon fractions, stimulated the total microbial and bacterial biomass in soil, and decreased methanogens/methanotrophs ratio, thereby reducing the CH_4 emissions (Fan et al., 2020). In addition, deep placement of N in reduced soil layer (anoxic layer) may retain N as NH_4^+ for a longer period of time that may mitigate CH_4 emissions by stimulating CH_4 oxidation (Gilbert and Frenzel, 1998; Bodelier et al., 2000). Results of this study are in close agreement with previous studies (Yao et al., 2017; Liu et al., 2020). However, lower CH_4 emissions in the PU treatment under AWD irrigation might be associated with the short-term increase of soil pH after urea hydrolysis and availability of excess NH_4^+, NO_3^-, and NO_2^- in the soil that could have stimulated CH_4 oxidation (Klüber and Conrad, 1998; Linquist et al., 2012).

AWD irrigation plays a significant role in mitigating CH_4 emissions from rice fields. In this study, on the average (across fertilizer treatments), AWD irrigation reduced CH_4 emissions by 28% over continuous flooding (CF) irrigation (Table 3). The mitigating effects were quite similar across fertilizer treatments suggesting that AWD irrigation is equally effective across range of fertilizer management practices. The highest percentage of CH_4 reduction was observed in the control treatment (30%) followed by UDP (29%), broadcast PU (29%), and IPNS treatments (26%), respectively. Our results are consistent with previous studies (Islam et al., 2020; Win et al., 2021). The efficacy of wetting and

Table 4

The effects of fertilizer × water regimes and year × water regimes on rice yield, total nitrogen uptake (TNU), agronomic efficiency of N (AE_N), and recovery efficiency of N (RE_N) in the Boro season.

Year	Fertilizer management	Grain yield (t ha^{-1})		Straw yield (t ha^{-1})		TNU (kg ha^{-1})		AE_N (kg grain kg^{-1} N)		RE_N (%)	
		Mean of 2 water regimes		Mean of 2 water regimes		Mean of 2 water regimes		Mean of 2 water regimes		Mean of 2 water regimes	
Fertilizer and water regimes interaction											
Mean	Control-N0	2.79c		2.77c		34.70d		–		–	
	UDP-N78	5.88a		5.73a		99.07a		39.6a		82.5a	
	PU-N78	4.86b		4.90b		75.41c		26.6c		52.2c	
	IPNS-N78	5.60a		5.40a		88.84b		36.1b		69.4b	
Year and water regimes interaction		AWD	CF			AWD	CF				
2018	Mean	4.61b	4.89a	4.69a		71.29b	81.36a	32.4a		68.3 ab	
2019		4.82a	4.85a	4.68a		69.96b	70.68c	34.9a		61.7b	
2020		4.80 ab	4.72a	4.74a		77.18a	76.57b	34.9a		74.1a	
Effects of water regimes		AWD	CF	AWD	CF	AWD	CF	AWD	CF	AWD	CF
Mean	Mean	4.75A	4.82A	4.59B	4.81A	72.81B	76.20A	33.7A	34.5A	66.3A	69.8A
ANOVA (p values)											
Water regimes (W)		0.1382		0.0551		0.0200		0.7047		0.3051	
Fertilizer (F)		0.0000		0.0000		0.0000		0.0000		0.0000	
Year (Y)		0.5891		0.8550		0.1172		0.7237		0.0824	
W × F		0.9788		0.7473		0.6786		0.9652		0.6993	
W × Y		0.0442		0.1003		0.0132		0.7819		0.6459	
F × Y		0.7086		0.3196		0.0819		0.5892		0.2760	
W × F × Y		0.9100		0.8183		0.9760		0.7780		0.9652	

Within a column, means followed by same lowercase letters and within a row for each response variable, means followed by the same uppercase letters are not significantly different at 5% level of probability by Tukeys's honest significant difference (HSD) test. UDP, PU, and IPNS indicate urea deep placement, prilled urea, and integrated plant nutrient system, respectively.

drying in reducing CH_4 emissions varies with the control of irrigation water, soil type, and other crop management practices (Xu et al., 2015; Liang et al., 2016). The reduction in CH_4 emission is associated with increased supply of oxygen during dry episodes, which makes the soil environment aerobic, where CH_4 could be oxidized by the methanotrophs. On the other hand, CF irrigation keeps the soil environment anoxic (redox potential lower than -150 mV), which enhances the anaerobic degradation of organic matter resulting in increased CH_4 emissions (Minamikawa et al., 2006).

4.2. N_2O emissions

N_2O emissions were sporadic and event-specific. Emissions were measured at weekly interval; therefore, some emission peaks after fertilizer application or during wet-dry episodes might have been missed. However, these results are inline with our previous studies where N_2O emissions were measured continuously—24 h a day, throughout the rice growing season (Gaihre et al., 2015, 2018; Islam et al., 2018a). The UDP and IPNS treatments increased cumulative N_2O emissions by 17% and 26%, respectively, compared to broadcast prilled urea (PU) (Table 3). Higher N_2O emissions in the UDP treatment under AWD irrigation are probably associated with the adequate supply of N and due to a favorable environment (alternate aerobic and anaerobic conditions) for microbial nitrification and subsequent denitrification (Das and Adhya, 2014; Islam et al., 2018a; Zou et al., 2007; Linquist et al., 2015). As urea was applied in the reduced zone, the N was retained in NH_4^+ form for a long time due to negligible losses through surface runoff and ammonia volatilization (Rochette et al., 2013; Islam et al., 2016, 2018c). Therefore, NH_4^+ retained in the sub-surface layer could be oxidized to NO_3^- through nitrification when there is oxygen supply during drying period, leading to greater N_2O emissions (Butterbach-Bahl et al., 2013). In contrast, UDP under continuous flooding (CF) irrigation reduced cumulative N_2O emissions by 49% and 53% compared to PU and IPNS treatments, respectively. Since deep placement in flooded soils significantly reduces floodwater NH_4^+-N, it leads to negligible N loss through NH_3 volatilization, nitrification, and denitrification (Liu et al., 2020). However, the IPNS treatment gave higher emissions in both irrigation regimes which might be associated with the combined application of PU with poultry manure that provides readily available C and N to the soil. In addition, PU supplies readily available N which played an important role as a precursor of nitrification and subsequent denitrification leading to a high amount of N_2O.

It is well documented that AWD irrigation increases N_2O emissions compared to continuous flooding (CF) irrigation (Islam et al., 2018a, 2020). The higher N_2O emissions from all treatments under AWD irrigation compared to CF condition are probably linked to the alternate oxic and anoxic conditions that might have enhanced the nitrification and subsequent denitrification processes, depending on the availability of oxygen. In contrast, emissions from continuously flooded fields are negligible probably due to the reduction of N_2O to N_2 by denitrification (Firestone and Davidson, 1989; Gaihre et al., 2015, 2018; Zou et al., 2005). However, the higher emission factor (EF) of N_2O from the integrated plant nutrient system (IPNS) treatment compared to urea deep placement (UDP) under CF irrigation is probably due to the increased availability of labile carbon, a finding that is consistent with earlier studies (Aguilera et al., 2013; Charles et al., 2017; Haque and Biswas, 2021). Higher EFs under AWD irrigation from UDP treatment have also been observed in previous studies (Islam et al., 2018a, 2020). Across the year and fertilizer treatments, higher EFs were found in AWD (0.41%) irrigation compared to CF (0.23%) irrigation. Similar results were reported by previous studies (Zou et al., 2007; Islam et al., 2020).

4.3. GWP and GHGI

An efficient method of N fertilizer application through UDP reduced the global warming potential (GWP) compared to the PU and IPNS treatments (Table 3). Although AWD irrigation had increased the N_2O emissions by 73% over CF condition, this increased emission was offset by the reduction of CH_4 emissions. Despite the higher radiative forcing of N_2O compared to CH_4, the amount of N_2O emissions is very small. Therefore, CH_4 played a vital role in contributing GWP in rice cultivation, accounting for over 90% of the total GWP (Sander et al., 2014; Islam et al., 2018b; Islam et al., 2020). In this study, the CH_4-induced GWP accounted for 98.8%, while N_2O-induced GWP was 1.2%. Results of this study suggest that UDP in combination with AWD irrigation could be a potential measure to reduce the GWP and greenhouse gas intensity in lowland rice cultivation.

4.4. Rice yield, nitrogen uptake and nitrogen use efficiency

The UDP and IPNS treatments produced significantly ($p < 0.05$) higher rice yields compared to the broadcast prilled urea (PU) treatment. The reasons behind the increased yields have already been explained by previous studies (Islam et al., 2016, 2018c; Kimani et al., 2020). For the integrated plant nutrient system (IPNS), the application of poultry manure might have improved the soil fertility through an increased supply of readily available C to the soil (due to low C:N ratio) and the release of N slowly synchronizing plant demand, thus, increasing plant growth including more effective tillers, volume of roots, and increased yield (Yadvinder-Singh et al., 2009; Lin et al., 2018; Sarkar et al., 2019). UDP also increased nitrogen use efficiency (NUE) compared to the broadcast PU and IPNS treatments as total N uptake increased under this treatment (Table 4). The increased yields and NUE observed in the UDP treatment is well documented (Islam et al., 2016, 2018c). The change in irrigation regime from CF to AWD had reduced emissions without affecting grain yield and NUE. These results suggest that AWD irrigation is effective in saving irrigation water with co-benefits of reducing GHG emissions (Dong et al., 2012; Lampayan et al., 2015; Islam et al., 2018c).

5. Conclusions

This study confirms that increasing nitrogen use efficiency by adopting improved fertilizer application method (urea deep placement, UDP) could reduce environmental pollution including mitigation of GHG emissions compared to conventional N management through broadcasting method or the adoption of integrated plant nutrient system (IPNS). Moreover, UDP could be more effective in mitigating GHG emissions when it is combined with AWD irrigation compared to continuous flooding (CF) irrigation. Similarly, UDP could reduce greenhouse gas intensity (GHGI) compared to conventional urea application or IPNS treatment. While comparing irrigation regimes, our results confirm that AWD irrigation could reduce GWP and GHGI without affecting NUE and yields compared to CF irrigation. Our findings suggest that adoption of UDP with AWD irrigation is effective in mitigating GHG emissions from rice based cropping system with similar soil types and management practices adopted in this study. Therefore, policy makers should develop strategies for wide-scale dissemination of both AWD and UDP technologies so that the country can mitigate GHG emissions while increasing NUE, and rice yield.

Credit author statement

S.M.M.I., Y.K.G. and U.S. designed the experiments. S.M.M.I., Y.K.G., M.R., M.N.A. and M.A. carried out the experiments. S.M.M.I. performed statistical data analysis. S.M.M.I., Y.K.G. and B.O.S. substantially contributed to results interpretation and writing the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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