Effects of integrated plant nutrition systems with fertilizer deep placement on rice yields and nitrogen use efficiency under different irrigation regimes

Article *in* Heliyon · December 2023

DOI: 10.1016/j.heliyon.2023.e23110

6 authors, including:


S.M. Mofijul Islam
Bangladesh Rice Research Institute
50 PUBLICATIONS **497** CITATIONS
SEE PROFILE


Yam Kanta Gaihre
International Fertilizer Development Center (IFDC)
80 PUBLICATIONS **1,320** CITATIONS
SEE PROFILE


Md. Rafiqul Islam
Bangladesh Rice Research Institute
217 PUBLICATIONS **1,089** CITATIONS
SEE PROFILE


Aminul Islam
Bangladesh Rice Research Institute
73 PUBLICATIONS **802** CITATIONS
SEE PROFILE

Heliyon 9 (2023) e23110

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Effects of integrated plant nutrition systems with fertilizer deep placement on rice yields and nitrogen use efficiency under different irrigation regimes

S.M. Mofijul Islam [a,*], Yam Kanta Gaihre [b], Md. Rafiqul Islam [a], Aminul Islam [a], Upendra Singh [b], Bjoern Ole Sander [c]

[a] *Soil Science Division, Bangladesh Rice Research Institute, Gazipur, Bangladesh*
[b] *International Fertilizer Development Center, Muscle Shoals, AL, 35661, USA*
[c] *International Rice Research Institute, Los Baños, Philippines*

ARTICLE INFO

Keywords:
Integrated plant nutrition systems
Poultry litter
Vermicompost
Urea deep placement
Water-saving irrigation
Nitrogen use efficiency

ABSTRACT

Improved fertilizer management, with a combination of organic and inorganic inputs, has the potential to enhance rice yield while maintaining soil health. However, studies on the effects of broadcast prilled urea (PU) and urea deep placement (UDP) applied in combination with organic inputs (poultry litter [PL] and vermicompost [VC]), as integrated plant nutrition systems (IPNSs), on rice yields and nitrogen use efficiency (NUE) under alternate wetting and drying (AWD) irrigation are limited. We conducted field experiments during the dry and wet seasons of 2018, 2019, and 2020 to investigate the effects of fertilizer treatments, including control (no nitrogen), UDP, PU, and IPNSs (PU + VC, PU + PL, and UDP + PL) on rice yield and NUE under two irrigation regimes – AWD and continuous flooding (CF). The results revealed that fertilizer treatment and irrigation regime had significant ($p < 0.05$) interaction effects on rice yield and the agronomic efficiency of N (AE_N) during the dry season. UDP significantly ($p < 0.05$) boosted rice yield, total dry matter (TDM), and NUE as compared to broadcast PU in both wet and dry seasons. Similarly, the IPNS treatment of UDP with PL significantly ($p < 0.05$) boosted rice yield, TDM, and NUE in comparison to broadcast PU. Under AWD irrigation, UDP alone produced higher rice yields than other treatments, while UDP, and UDP with PL produced similar yields under CF irrigation. During the dry season, AWD irrigation significantly ($p < 0.05$) increased rice yield, TDM, and AE_N when compared to CF conditions, but during the wet season, AWD irrigation demonstrated a rice yield and NUE equivalent to CF. This research implies that using a UDP alone or in combination with PL as an IPNS could be a good way to boost crop productivity while also maintaining soil fertility.

1. Introduction

Rice is an important cereal crop for world food security. It serves as about 20 % of the energy source for more than 50 % of the world population [1]. In Bangladesh, rice is cultivated in two to three seasons every year and covers 11.4 million hectares (ha) of land,

---

* Corresponding author. Soil Science Division Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh.
E-mail addresses: mislambrri@gmail.com (S.M.M. Islam), ygaihre@ifdc.org (Y.K. Gaihre), rafiqbrri@yahoo.com (Md.R. Islam), aminbrri@gmail.com (A. Islam), usingh@ifdc.org (U. Singh), b.sander@irri.org (B.O. Sander).

https://doi.org/10.1016/j.heliyon.2023.e23110
Received 9 November 2022; Received in revised form 18 November 2023; Accepted 22 November 2023

yielding 36.6 million metric tons (mt) in 2019–20 [2]. Boro, or dry season rice (December/January to April/May), contributes more than 50 % (19.6 million mt) of the total annual production, covering about 4.8 million ha. Boro rice requires relatively high doses of fertilizers compared to the Aus (pre-monsoon) and Aman (monsoon) seasons. The average rice yield increment for the last 40 years (1979-80 to 2019–20) was higher in the dry Boro season (37 %) compared to the wet seasons, Aus (25 %) and Aman (31 %).

Nitrogen (N) fertilizer plays an important role in sustainable rice production. But excessive and improper use of N fertilizers is associated with low nitrogen use efficiency (NUE), contributing to environmental pollution and increased greenhouse gas (GHG) emissions [3–9]. Nitrogen losses to the environment are higher when it is applied through a broadcast method. Improper fertilizer application is associated with degradation of the soil's physical, chemical, and biological qualities, resulting in poor soil fertility [10–12]. Therefore, it is necessary to find an alternative fertilizer management strategy to boost crop productivity and ameliorate soil fertility, particularly under the current scenario of the international fertilizer crisis. Farmers' access to chemical fertilizers is poor due to the increasing price of chemical fertilizers in the international market. The Government of Bangladesh has given a significant amount of subsidy on fertilizers to increase crop production, which not only poses a financial burden but also increases environmental pollution due to excessive use of fertilizers. Therefore, the integrated use of organic inputs and inorganic fertilizers, known as an integrated plant nutrition system (IPNS), might be an alternative for reducing the use of chemical fertilizers while increasing rice yield and maintaining soil fertility and soil health.

The application of organic inputs can ensure balanced fertilization by providing both macro and micronutrients. Application of organic inputs can increase soil organic matter and improve physical, chemical, and biological characteristics, leading to a greater supply of nutrients [13,14]. Organic inputs, such as poultry litter (PL) and vermicompost (VC), release N slowly, improve crop productivity, and help in maintaining sustainable soil health [15–17]. In addition, the incorporation of organic inputs provides other nutrients, including total potassium (K), total phosphorus (P), and micronutrients [14,18], and can reduce soil bulk density, improve soil porosity, and increase water-holding capacity, resulting in improved soil physical properties [19]. In addition, organic inputs can decrease the leaching loss of nutrients and increase the nutrient retention capacity of the soil [20]. In contrast, due to the relatively low nutrient content of organic inputs, these cannot provide sufficient nutrients to meet the plant's demands. Therefore, the combined application of organic and inorganic fertilizer, i.e., IPNS, is considered a sustainable approach to improving crop productivity and soil fertility [14,17]. The IPNS approach could be used to reduce the use of inorganic fertilizer for the establishment of a balanced linkage between fertilizer inputs and crop demands. PL and VC are locally available sources of organic inputs in Bangladesh. Many studies have shown that the integrated use of organic inputs in combination with 50 % of the recommended NPK from inorganic fertilizer improves soil pH, bulk density, water-holding capacity, aggregate stability, electrical conductivity (EC), cation exchange capacity (CEC), soil organic matter, total N, available P and K, microbial biomass N, and enzymatic activities [15,17,18,21–23]. Similarly, IPNS could increase crop yield, total nitrogen uptake (TNU), and NUE. Therefore, IPNSs might be considered an effective tool for sustainable crop production as they maintain soil fertility and restore soil health. However, most of the previous studies were conducted with either organic inputs solely or the addition of organic inputs with the recommended inorganic fertilizer [18,23–25]. The present investigation introduced PL- and VC-based IPNS, in which amounts of organic and inorganic fertilizer were customized at a 1:1 ratio based on the nutrient content calculation of the organic input.

Fertilizer use efficiency and its effects on crop yields can be influenced by several other management factors, including irrigation. Generally, rice is cultivated with continuous flooding (CF) irrigation. Alternate wetting and drying (AWD) is an irrigation technology that has multiple benefits, such as saving water by up to 30 % and reducing CH_4 emissions and the arsenic (As) content of grain [7,8,26,27]. The impacts of AWD on rice yield vary according to the agroecological zone and management practice. Other conditions, such as the degree of soil dryness, the type of soil, the timing of irrigation, climatic factors during the rice-growing season, soil hydrological conditions, N fertilizer management, and rice cultivars, all have an impact on yield [5,28–31]. Due to water scarcity and a depleting groundwater table, AWD irrigation is gaining popularity in Bangladesh [26,32]. Previous findings have shown that AWD irrigation with urea deep placement (UDP) increases yields and NUE due to improved root morphology and increased oxygen concentration in the rhizosphere soil, which contributes to maintaining the appropriate ratio of NH_4^+/NO_3^- [29,31,33]. In contrast, under CF conditions, UDP retains most of the N as non-exchangeable NH_4^+-N in the root zone, providing N throughout the rice growing season [34]. The dry-wet episodes of AWD irrigation change the soil properties and the fate of soil N, particularly the dynamics of carbon (C) and N. In general, AWD irrigation increases the mineralization rate of C and N, resulting in increased nutrient loss. But studies on the effects of AWD irrigation with various fertilizer management practices on rice yield and NUE are contradictory [5,30,31,35,36]. Islam et al. [30] reported that fertilizer treatment had a significant interaction effect on rice yield NUE. In contrast, Dong et al. [36] observed that AWD irrigation significantly reduced NUE due to increased NH_3 volatilization compared to CF irrigation. In addition, the effects of IPNS, especially the combined application of organic (PL/VC) and inorganic (PU/UDP) fertilizers, on rice yield and NUE under AWD irrigation are unknown. Thus, further research is needed to determine the effects of IPNS-based chemical fertilizers with various irrigation regimes on rice yield and NUE under different agroecological zones of Bangladesh. This type of research will be important in achieving higher rice yields, maintaining soil fertility, and providing insights into the process behind the interplay between IPNS and irrigation regime for sustainable rice farming.

Therefore, this study was conducted to determine the effects of chemical fertilizer in IPNS treatments, as well as the interactions with different irrigation regimes (AWD versus CF), on rice yield and NUE. It is hypothesized that the sole application of UDP as part of an IPNS under AWD irrigation could boost rice yield and NUE compared to broadcast PU and IPNS treatment under CF irrigation.

2. Materials and methods

2.1. Experimental site and weather conditions

The field experiments were carried out at Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh (latitude: 23°59'25", longitude: 90°24'33"), for nine consecutive rice growing seasons across three years (2018–2020). There were three rice growing seasons (Aus, Aman, and Boro) in each year. The Aus season lasts from April/May to July/August, whereas the Aman season lasts from July/August to November/December. Most of the rice grown during the Aus and Aman seasons is rainfed, though some supplementary irrigation may be needed in the early Aus season and the late Aman season. Boro, on the other hand, is a dry season in which rice is cultivated from December/January to April/May and is fully reliant on irrigation. The experiment site has a humid sub-tropical monsoon climate. The mean annual rainfall is around 2000 mm, with the majority of it falling between June and October. Fig. 1 depicts daily rainfall and mean air temperatures over the course of the trial. The soil organic carbon content of post-harvest soil of Boro 2020 for each treatment is presented in Table 1 and the physicochemical properties of the soil are given in Table S1.

2.2. Experimental design and treatments

Seven fertilizer treatments with different organic and inorganic nutrient sources and N rates in different seasons are presented in Table 2. These treatments were arranged in a split-plot design with three replications, where water management was considered as the main plot and fertilizer treatments as sub-plots. The sources of N fertilizer were prilled urea (PU), urea deep placement (UDP), poultry litter (PL), and vermicompost (VC). The N rates for Aus and Aman seasons were similar at 52–78 kg ha^{-1}, while the rate for the Boro season was 78–104 kg N ha^{-1} (Table 2). All fertilizer treatments were tested under two different irrigation regimes – AWD and CF. For

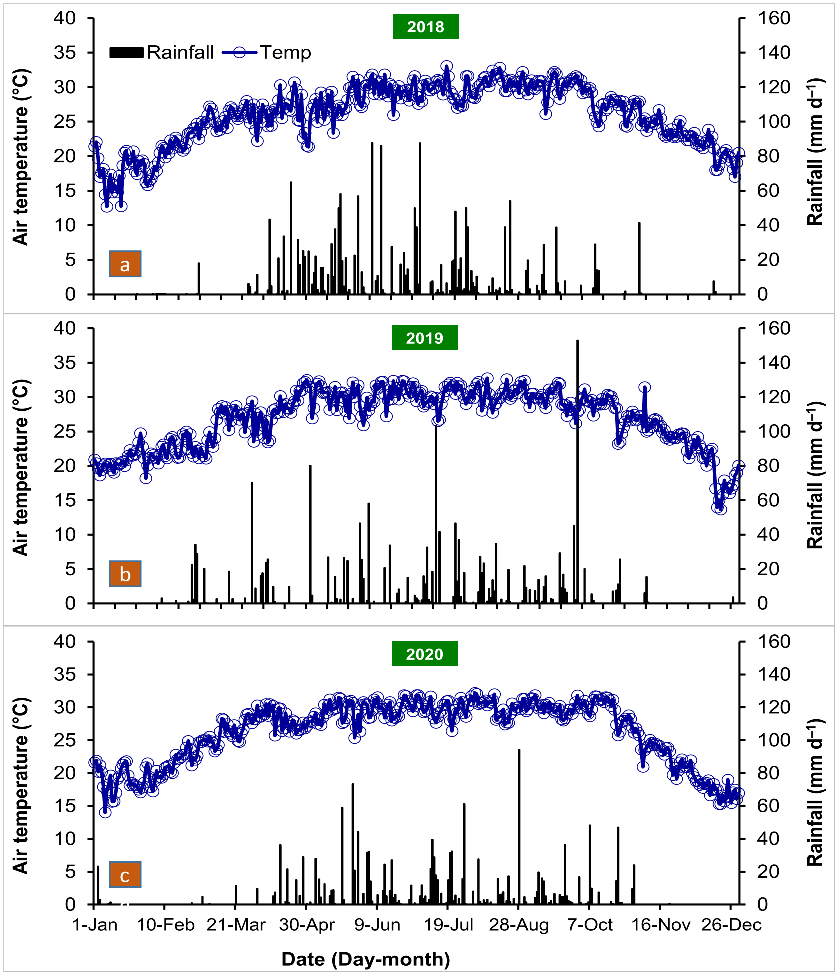

Fig. 1. Daily average rainfall and air temperature for the Aus, Aman, and Boro seasons of 2018, 2019, and 2020 during the trial period. a, b, and c indicate air temperature and rainfall in the year 2018, 2019, and 2020, respectively. (Data source: Weather station, Bangladesh Rice Research Institute, Gazipur).

Table 1

The soil organic carbon content (SOC) of post-harvest soil of Boro 2020 for each treatment at BRRI farm, Gazipur.

Treatments	SOC (%)	Analysis method	Comment
Control-N0	1.35	Wet oxidation	Initial SOC: 1.31 %
UDP-N52	1.42		
PU-N52	1.37		
PU-N78	1.39		
IPNS-N52 (PU + VC)	1.51		
IPNS-N52 (UDP + PL)	1.57		
IPNS-N52 (PU + PL)	1.54		

UDP, PU, VC, PL, and IPNS refer to the urea deep placement, prilled urea, vermicompost, poultry litter, and integrated plant nutrition system, respectively.

Table 2

Treatments description used in this study.

Treatments	Description	N rate (kg ha^{-1})		
		Aus	Aman	Boro
Control	N control	0	0	0
UDP	Urea deep placement	52	52	78
PU	Prilled urea	52	52	78
PU	Prilled urea	78	78	104
IPNS (PU + VC)	PU with vermicompost (VC) as integrated plant nutrition systems (IPNS)	52	52	78
IPNS (UDP + PL)	UDP with poultry litter (PL) as IPNS	52	52	78
IPNS (PU + PL)	PU with PL as IPNS	52	52	78

the UDP treatment, three sizes of briquettes (0.9 g, 1.8 g, and 2.7 g) were used as per the treatment and required N rate. Briquettes were buried 8–10 cm deep in the middle of four rice hills, spaced 40 cm apart (62,500 placement sites per hectare). With this spacing, the application of 0.9 g, 1.8 g, and 2.7 g briquettes provided 26, 52, and 78 kg N ha^{-1}, respectively. Deep placement was performed 7–10 days after transplanting (DAT) the rice, when puddled soil was settled. Each experimental plot had dimensions of 4.8 m × 3.2 m.

2.3. Crop management

In the Aus and Aman seasons, the complete amount of PU was broadcast in two equal splits at 7–10 DAT and 25–30 DAT, while in the Boro season, PU was applied in three equal splits at 7–10 DAT and at maximum tillering and panicle initiation stages. In the IPNS treatments, 50 % of the total N was supplied through inorganic fertilizer and organic inputs provided the remaining 50 % N. The recommended fertilizer rates of P, K, sulfur (S), and zinc (Zn) were 10, 50, 6, and 0 kg ha^{-1} in the Aus-Aman seasons and 15, 75, 10, and 1 kg ha^{-1} in the Boro season (FRG, 2018). There was some variation in the rates of P, K, and S fertilizers in the organic inputs. Therefore, additional P and S were not required from chemical fertilizer in those treatments including organic inputs, while K fertilizer was required in the organic input treatments. After calibration of organic input nutrients, K (muriate of potash, MoP) fertilizer was used as basal during the final land preparation in PL- and VC-treated plots at 53 g and 91 g, respectively, in the Aus and Aman seasons and at 126 g and 129 g, respectively, in the Boro seasons. During final land preparation, well-decomposed (air-dried) PL and VC were incorporated into the soil. The nutrient status of PL and VC is presented in Table 3.

Two to three rice seedlings were transplanted at 20 × 20 cm distance. Crop varieties were BRRI dhan65, BRRI dhan62, and BRRI dhan28 for the Aus, Aman, and Boro seasons, respectively. P (triple superphosphate, TSP), K (MoP), S (gypsum), and Zn (zinc sulfate) fertilizers were used as basal during final field preparation in all plots, except the sole organic input plots. The organic input plots receive K, S, and Zn fertilizer.

The CF plots were irrigated continuously until two weeks prior to harvest, whereas the AWD plots were irrigated according to the safe AWD principle [26]. At 10 DAT, a perforated PVC pipe (15 cm depth) was placed in each AWD plot to monitor floodwater depth. Daily monitoring for floodwater level was performed within the PVC pipe, and irrigation was applied once the water level in the AWD

Table 3

The nutrient status (%) of poultry litter and vermicompost.

Organic manures/nutrient content (%)	Poultry litter		Vermicompost	
	Aus-Aman	Boro	Aus-Aman	Boro
C	13	12	23	20
N	1.21	1.15	1.69	1.55
P	1.15	1.10	0.67	0.65
K	0.91	0.89	0.82	0.79
S	0.38	0.37	0.33	0.35
C: N	10.5	10.7	13.7	12.9

pipe dropped 12–15 cm below the soil surface (Fig. 2). The monsoon rains in the Aus and Aman seasons disturbed the AWD cycle even though the floodwater depth was checked regularly to schedule irrigation and maintain the AWD cycle. However, plots were irrigated continuously for a week following topdressing with PU during the flowering stage, regardless of whether they were managed using AWD or CF.

2.4. Rice yield and NUE

For grain and straw yield, rice plants from 5 m^2 areas in the middle of each plot were harvested at ground level. Harvested rice plants were threshed and grains were cleaned by the winnowing method. The grain yield was adjusted to a moisture level of 14 %. The grain and straw samples were prepared and analyzed for total N content using the micro-Kjeldahl method [37] to quantify the total N uptake by plant and estimate NUE. The NUE, including the agronomic efficiency of N (AE_N; kg grain kg^{-1} N applied) and recovery efficiency of N (RE_N; kg N uptake per kg^{-1} N applied), was determined for all treatments, as described by Singh et al. [38].

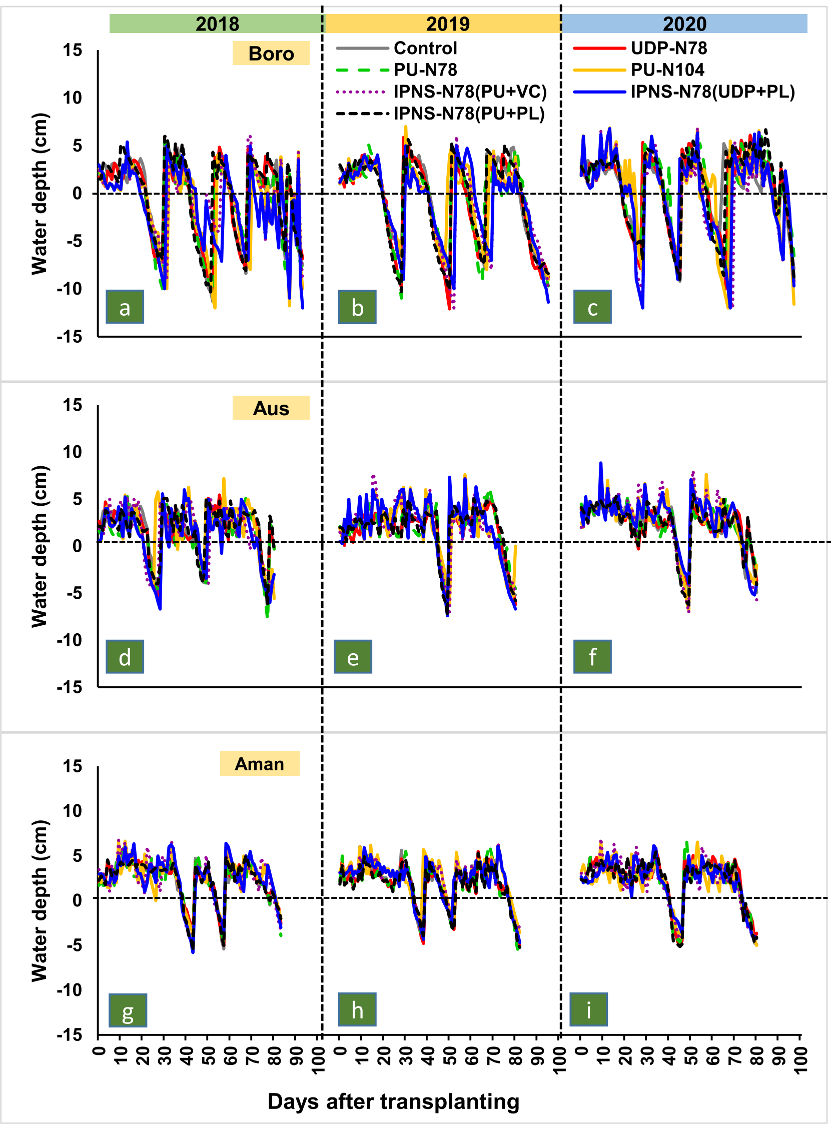

Fig. 2. Daily field water depth from transplanting to the harvesting of rice plants in the Aus, Aman, and Boro seasons under AWD irrigation. UDP, PU, PL, VC, and IPNS denote urea deep placement, prilled urea, poultry litter, vermicompost, and integrated plant nutrition system, respectively. a-c, d-f, and g-i indicate water depth in the Boro, Aus, and Aman seasons, respectively.

2.5. Data analysis

The Statistical Tool for Agricultural Research (STAR 2.0.1, International Rice Research Institute, Philippines) was used to perform an analysis of variance (ANOVA) for each response variable (grain yield, straw yield, total N uptake, and NUE) following the standard protocol, as described by Gomez and Gomez [39]. The irrigation regime was the main plot and fertilizer treatments were the sub-plots; the year was pooled in an ANOVA with a split-plot structure. As differences among rice growing seasons were obvious, analysis was run individually for the Aus, Aman, and Boro seasons. A combined ANOVA was performed for Aus, Aman, and Boro for each crop year to see the interaction of treatment with year. Treatment means were compared using Tukey's honest significant difference (HSD) test at the 5 % significance level.

3. Results

3.1. Grain yield and aboveground biomass

Application of N fertilizer, irrespective of rate or source, significantly ($p < 0.05$) increased panicle production per unit area, grain yield, and straw yield compared to the control treatment. IPNS with UDP considerably ($p < 0.05$) increased grain yield by about 15–30 % in Aus and 5–10 % in Aman over PU at 52 kg N ha^{-1} and PU with either VC or PL (Tables 4 and 5). Similarly, the IPNS with UDP treatment significantly ($p < 0.05$) increased straw yield by about 14–21 % in the Aus season compared to PU and IPNS with PL at 52 kg N ha^{-1}, while no significant variation in straw yield was observed among the treatments in the Aman seasons (Tables 4 and 5). UDP at 52 kg N ha^{-1} showed a rice yield similar to the higher N rate (78 kg ha^{-1}) of broadcast PU. However, there was no significant variation in grain yield or total dry matter (TDM) between UDP alone and UDP with PL as an IPNS treatment. Grain yields and TDM were similar in the Aus season across the three years, while grain yields and TDM were lower in the Aman season in 2018 compared to 2019. AWD irrigation showed similar rice yields with CF irrigation in both the Aus and Aman seasons, regardless of year or fertilizer treatment (Tables 4 and 5).

Interaction effects between fertilizer treatments and water regimes on grain yield and aboveground TDM were significant ($p < 0.05$) in the Boro season (Table 6). UDP with PL produced significantly ($p < 0.05$) higher grain yield by 12–14 % in AWD irrigation and by 17–18 % in CF irrigation than PU and PU with VC at 78 kg N ha^{-1}. In AWD irrigation, UDP significantly ($p < 0.05$) increased grain yield by 7–22 % irrespective of treatment, while in CF irrigation, UDP showed a higher yield (9–21 %) compared to PU and PU with PL or VC as IPNS treatments (Table 6). However, AWD irrigation significantly increased grain yield over CF under UDP treatment at 78 kg N ha^{-1}. UDP with PL gave significantly ($p < 0.05$) greater TDM by about 11–14 % in AWD irrigation and by about 20–21 % compared to PU and PU with VC at 78 kg N ha^{-1} (Table 6). Broadcast PU at 104 kg N ha^{-1} showed grain yield and TDM comparable with the combined application of PU and PL as an IPNS treatment at 78 kg N ha^{-1} under both water regimes (Table 6). There was no significant

Table 4
The impacts of fertilizer, irrigation regimes and year on panicles, grain yield, straw yield, and aboveground total dry matter (TDM) in the Aus season.

Fertilizer management	Year	Panicle (m^{-2})		Grain yield (t ha^{-1})		Straw yield (t ha^{-1})		TDM (t ha^{-1})	
		Mean of irrigation regimes		Mean of irrigation regimes		Mean of irrigation regimes		AWD	CF
Effects of fertilizer (mean across year and irrigation regimes)									
Control-N0	Mean	249c		2.8e		2.9e		5.7e	5.6e
UDP-N52		338a		3.6abc		3.8bc		7.4abc	7.5 ab
PU-N52		287b		3.0e		3.3d		6.4d	6.1d
PU-N78		321 ab		3.8 ab		4.1a		7.8 ab	8.0a
IPNS-N52 (PU + VC)		306 ab		3.4cd		3.7bc		7.2c	7.0c
IPNS-N52 (UDP + PL)		343a		3.9a		4.0 ab		8.0a	7.8a
IPNS-N52 (PU + PL)		307 ab		3.4d		3.5cd		7.2c	6.6cd
Effects of the year (mean across fertilizer and irrigation regimes)									
Mean	2018	318		3.4		3.7		7.1	
	2019	299		3.4		3.6		6.9	
	2020	305		3.4		3.6		7.0	
Effects of irrigation regimes (means across fertilizer and year)									
		AWD	CF	AWD	CF	AWD	CF	AWD	CF
Mean	Mean	305	309	3.4	3.3	3.7A	3.5B	7.1A	6.9B
ANOVA (p values)									
Irrigation (I)		ns		ns		*		*	
Fertilizer (F)		*		*		*		*	
Year (Y)		ns		ns		ns		ns	
I × F		ns		ns		ns		*	
I × Y		ns		ns		ns		ns	
F × Y		ns		ns		ns		ns	
I × F × Y		ns		ns		ns		ns	

Tukey's honest significant difference (HSD) test indicates that the means denoted by the same lowercase letter or uppercase letter inside a column or row for the same response variable are not statistically different from one another at the 5 % level of probability. The abbreviations UDP, PU, VC, PL, and IPNS refer to the urea deep placement, prilled urea, vermicompost, poultry litter, and integrated plant nutrition system, respectively. * and ns indicate statistically significant and non-significant at the 5 % level of probability.

Table 5

The impacts of fertilizer, irrigation regimes and year on panicles, grain yield, straw yield and aboveground total dry matter (TDM) in the Aman season.

Fertilizer management	Year	Panicle (m^{-2})		Grain yield (t ha^{-1})		Straw yield (t ha^{-1})		TDM (t ha^{-1})	
		Mean of irrigation regimes		Mean of irrigation regimes		Mean of irrigation regimes		Mean of irrigation regimes	
Effects of fertilizer (mean across year and irrigation regimes)									
Control-N0	Mean	237c		3.5c		3.4b		6.9c	
UDP-N52		347a		4.4a		4.5a		8.9a	
PU-N52		304b		4.1b		4.2a		8.3b	
PU-N78		318b		4.5a		4.4a		8.9a	
IPNS-N52 (PU + VC)		300b		4.1b		4.2a		8.4b	
IPNS-N52 (UDP + PL)		351a		4.5a		4.3a		8.8a	
IPNS-N52 (PU + PL)		319b		4.3 ab		4.3a		8.7 ab	
Effects of the year (mean across fertilizer and irrigation regimes)									
Mean	2018	333a		4.1		4.2		8.3b	
	2019	303b		4.3		4.3		8.5a	
	2020	296b		4.3		4.2		8.5 ab	
Effects of irrigation regimes (means across fertilizer and year)									
		AWD	CF	AWD	CF	AWD	CF	AWD	CF
Mean	Mean	312	309	4.2	4.1	4.2	4.2	8.5	8.3
ANOVA (p values)									
Irrigation (I)		ns		ns		ns		ns	
Fertilizer (F)		*		*		*		*	
Year (Y)		*		ns		ns		*	
I × F		ns		ns		ns		ns	
I × Y		ns		ns		ns		ns	
F × Y		ns		ns		ns		ns	
I × F × Y		ns		ns		ns		ns	

Tukey's honest significant difference (HSD) test indicates that the means denoted by the same lowercase letter or uppercase letter inside a column or row for the same response variable are not statistically different from one another at the 5 % level of probability. The abbreviations UDP, PU, VC, PL, and IPNS refer to the urea deep placement, prilled urea, vermicompost, poultry litter, and integrated plant nutrition system, respectively. * and ns indicate statistically significant and non-significant at the 5 % level of probability.

Table 6

The impacts of fertilizer, irrigation regimes, and year on panicles, grain yield, straw yield, and aboveground total dry matter (TDM) in the Boro season.

Fertilizer management	Year	Panicle (m^{-2})		Grain yield (t ha^{-1})		Straw yield (t ha^{-1})		TDM (t ha^{-1})	
		Mean of irrigation regimes		AWD	CF	AWD	CF	AWD	CF
Fertilizer and irrigation regimes interaction									
Control-N0	Mean	225e		2.6 dA	2.7eA	2.6 dA	2.6 cA	5.2 dA	5.3 dA
UDP-N78		348a		6.1 aA	5.8 aB	5.8 aA	5.7 aA	12.0 aA	11.4 aB
PU-N78		295cd		5.0 cA	4.8 dA	4.9 cA	4.7bA	9.9 cA	9.5 cA
PU-N104		320abc		5.6bA	5.7abA	5.4abA	5.5 aA	11.0bA	11.2abA
IPNS-N78 (PU + VC)		268d		5.1 cA	4.9cdA	5.1bcA	4.6bB	10.2 cA	9.6 cB
IPNS-N78 (UDP + PL)		329 ab		5.7bA	5.8 aA	5.6 aA	5.7 aA	11.3abA	11.5 aA
IPNS-N78 (PU + PL)		304bc		5.7bA	5.3bcB	5.7 aA	5.2 aB	11.5abA	10.5bB
Effects of the year (mean across fertilizer and irrigation regimes)									
Mean	2018	294		5.0		4.8b		9.8b	
	2019	299		5.1		5.0 ab		10.1a	
	2020	303		5.1		5.1b		10.2a	
Effects of irrigation regimes (means across fertilizer and year)									
		AWD	CF	AWD	CF	AWD	CF	AWD	CF
Mean	Mean	296	301	5.1A	5.0B	5.0A	4.9B	10.1A	9.9B
ANOVA (p values)									
Irrigation (I)		ns		*		*		*	
Fertilizer (F)		*		*		*		*	
Year (Y)		ns		ns		*		*	
I × F		ns		*		*		*	
I × Y		ns		ns		ns		ns	
F × Y		ns		ns		ns		*	
I × F × Y		ns		ns		ns		ns	

Tukey's honest significant difference (HSD) test indicates that the means denoted by the same lowercase letter or uppercase letter inside a column or row for the same response variable are not statistically different from one another at the 5 % level of probability. The abbreviations UDP, PU, VC, PL, and IPNS refer to the urea deep placement, prilled urea, vermicompost, poultry litter, and integrated plant nutrition system, respectively. * and ns indicate statistically significant and non-significant at the 5 % level of probability.

variation in grain yield over the three years. However, fertilizer treatments had a significant effect with year on TDM in Boro season (Table 6). TDM was higher in 2019 and 2020 compared to 2018 under PU at 78 and 104 kg N ha^{-1} and PU with VC. When compared to CF, AWD irrigation significantly ($p < 0.05$) increased rice yield and TDM across the years and fertilizer treatments (Table 6).

3.2. *Nitrogen uptake and nitrogen harvest index*

Fertilizer treatments had significant ($p < 0.05$) effects on total N uptake (TNU) for each of the three growing seasons (Tables 7–9), while N harvest index (NHI) was significant ($p < 0.05$) in Aus and Boro seasons (Tables 7 and 9). UDP significantly ($p < 0.05$) increased TNU by about 22 % in Aus, 17 % in Aman, and 30 % in Boro compared to broadcast PU at a similar N rate (Tables 7–9). However, the difference in NHI was insignificant ($p > 0.05$) between the PU and UDP treatments in all seasons (Tables 7–9). Among the IPNSs, UDP with PL significantly ($p < 0.05$) increased TNU by about 16–18 % in Aus, 3–15 % in Aman, and 6–23 % in Boro compared to PU with PL and PU with VC, while the difference in NHI was insignificant ($p > 0.05$) (Tables 7–9). TNU was comparable between UDP alone, UDP as an IPNS at a lower N rate (52 kg ha^{-1} in Aman and 78 kg N ha^{-1} in Boro), and broadcast PU at a higher N rate (78 kg ha^{-1} in Aman and 104 kg N ha^{-1} in Boro). TNU was higher in 2018 in the Aus season, while it was lower in 2018 in the Aman season (Tables 7 and 8). Similarly, TNU was higher in the Boro season in 2018 and 2020 compared to 2019. Across the years and fertilizer treatments, there was significant variation in TNU and NHI between the two irrigation regimes (Tables 7–9).

3.3. *Nitrogen use efficiency*

Both the AE_N and RE_N were affected by fertilizer treatment during the Aus and Aman seasons (Tables 7 and 8). In Aus and Aman seasons, UDP alone or in combination with PL significantly ($p < 0.05$) increased NUE (AE_N and RE_N) compared to broadcast PU at a similar N rate or PU with VC. Across the years and fertilizer treatments, AWD irrigation produced similar AE_N and RE_N values with CF conditions in Aus and Aman seasons (Tables 7 and 8).

Water management had significant ($p < 0.05$) interaction effects with fertilizer treatments on AE_N in the Boro season (Table 9). UDP alone or in combination with PL significantly ($p < 0.05$) increased AE_N compared to broadcast PU under CF irrigation, but IPNS treatments had no significant effects under AWD irrigation (Table 9). The highest RE_N was observed in UDP alone and UDP with PL as an IPNS treatment compared to the other treatments (Table 9). Higher AE_N and RE_N were observed in 2020 compared to 2018 and 2019. Across the fertilizer treatments and years, the highest AE_N and RE_N values were observed in AWD irrigation compared to the CF irrigation in the Boro season (Table 9).

4. Discussion

4.1. *Grain yield and aboveground biomass*

The combined application of organic inputs and inorganic fertilizer plays a key role in improving rice yield compared to the sole application of broadcast chemical fertilizers at similar N rates. Application of poultry litter with urea deep placement or prilled urea increased rice yield and total aboveground dry matter compared to PU at similar N rates in Aus (wet) and Boro (dry) seasons (Tables 4 and 6). These results are in close agreement with previous findings [8,9,15,17,23]. In IPNS treatments, the consistent supply of dissolved organic carbon and nitrogen to the soil due to slow mineralization of organic inputs might have synchronized N supply with plant demand, thus increasing rice yield and TDM. In addition, the slow and gradual release of N from organic sources is an extra advantage over the single application of chemical fertilizer for getting higher yields [17,18]. Increasing the N supply could help to increase effective tiller production, which could lead to higher rice yield [15–17,21]. In addition, UDP applied in anaerobic soil layers (anaerobic zone) ensures prolonged N availability and enhanced biological N fixation, which promotes root growth and effective tillers, thus resulting in higher rice yield and TDM [5,30,34]. Further, the higher yields and TDM in the UDP treatment compared to PU treatment (Tables 4–6) could be due to the increase the contact of clay particles with fertilizer granules leading to reduce NH_4^+-N concentration in floodwater, thus reduction in N loss through volatilization and surface runoff [5,30,40,41]. Hence, the application of UDP, either solely or combined with PL, could play a significant role in improving rice yield. Moreover, organic inputs can improve the biological properties of soil, particularly enhancing microbial biomass carbon and soil enzymatic activities that could be participating in the microbial decomposition of organic matter and nutrient turnover [15,42]. Microbial biomass carbon provides a steady source of C to microbes, resulting in an improvement in soil health [15,18,43]. Long-term application of organic inputs increases CEC and bulk density and improves soil aeration [15,44]. However, no additional advantage of using vermicompost over poultry litter as part of IPNS was found in this study for Boro season (Table 6). As VC contains a relatively higher C:N ratio compared to PL (Table 3), the mineralization of VC could be relatively slower than PL, which could be delaying nutrient availability at the early stage of the rice plant. Thus, the plant would suffer nutrient shortage at the early stage of rice growth, which might be associated with reduced tiller and panicle production, resulting in lower yield [17,21].

Previous findings on the impacts of AWD on rice yield are inconsistent and inconclusive [5,29,31,35,36]. However, in this study, we found a significant ($p < 0.05$) relationship between fertilizer management and water regime with rice yield in Boro season and TDM production during Aus and Boro season (Tables 4 and 6). AWD irrigation substantially ($p < 0.05$) enhanced rice yield and TDM compared to CF when N fertilizer was deep-placed (Table 6), which is in good agreement with previous findings [30,45]. A larger yield increment from the UDP treatment under AWD practice is probably related to higher panicle production and higher NUE (Table 9). On the other hand, AWD irrigation showed a rice yield and TDM similar to CF when N fertilizer was applied as broadcast PU, while AWD

Table 7

The impacts of fertilizer, irrigation regimes and year on total nitrogen uptake (TNU), N harvest index (NHI), agronomic efficiency (AE_N) and recovery efficiency of N (RE_N) in the Aus season.

Fertilizer management	Year	TNU (kg ha^{-1})		NHI		AE_N (kg grain kg^{-1} N)		RE_N (%)	
		Mean of irrigation regimes		Mean of irrigation regimes		Mean of irrigation regimes		Mean of irrigation regimes	
Effects of fertilizer (mean across year and irrigation regimes)									
Control-N0	Mean	39.6e		0.57c		–		–	
UDP-N52		64.3b		0.63a		17.0 ab		50a	
PU-N52		52.6d		0.60 ab		4.7c		27c	
PU-N78		71.1a		0.60 ab		13.4b		42b	
IPNS-N52 (PU + VC)		56.7cd		0.61 ab		12.5b		35b	
IPNS-N52 (UDP + PL)		66.7b		0.60 ab		22.6a		54a	
IPNS-N52 (PU + PL)		57.6c		0.60 ab		11.4b		37a	
Effects of the year (mean across fertilizer and irrigation regimes)									
Mean	2018	61.0a		0.60a		15.6a		46a	
	2019	56.7b		0.60a		13.0a		48a	
	2020	57.4b		0.60a		12.2a		47a	
Effects of irrigation regimes (means across fertilizer and year)									
		AWD	CF	AWD	CF	AWD	CF	AWD	CF
Mean	Mean	58.9	57.8	0.60	0.60	13.5	13.7	40	41
ANOVA (p values)									
Irrigation (I)		ns		ns		ns		ns	
Fertilizer (F)		*		*		*		*	
Year (Y)		*		ns		ns		ns	
I × F		ns		ns		ns		ns	
I × Y		ns		ns		ns		ns	
F × Y		ns		ns		ns		ns	
I × F × Y		ns		ns		ns		ns	

Tukey's honest significant difference (HSD) test indicates that the means denoted by the same lowercase letter or uppercase letter inside a column or row for the same response variable are not statistically different from one another at the 5 % level of probability. The abbreviations UDP, PU, VC, PL, and IPNS refer to the urea deep placement, prilled urea, vermicompost, poultry litter, and integrated plant nutrition system, respectively. * and ns indicate statistically significant and non-significant at the 5 % level of probability.

Table 8

The impacts of fertilizer, irrigation regimes and year on total nitrogen uptake (TNU), N harvest index (NHI), agronomic efficiency (AE_N) and recovery efficiency of N (RE_N) in the Aman season.

Fertilizer management	Year	TNU (kg ha^{-1})		NHI		AE_N (kg grain kg^{-1} N)		RE_N (%)	
		Mean of irrigation regimes		Mean of irrigation regimes		Mean of irrigation regimes		Mean of irrigation regimes	
Effects of fertilizer (mean across year and irrigation regimes)									
Control-N0	Mean	49.7c		0.59a		–		–	
UDP-N52		80.1a		0.60a		17.7a		58a	
PU-N52		68.4b		0.62a		11.9b		36b	
PU-N78		80.0a		0.60a		12.6b		39b	
IPNS-N52 (PU + VC)		69.2b		0.62a		12.2b		37b	
IPNS-N52 (UDP + PL)		79.9a		0.63a		18.7a		58a	
IPNS-N52 (PU + PL)		77.5a		0.62a		15.7 ab		53a	
Effects of the year (mean across fertilizer and irrigation regimes)									
Mean	2018	67.9b		0.57c		14.1		46	
	2019	75.8a		0.65a		14.7		48	
	2020	72.7a		0.62b		15.5		47	
Effects of irrigation regimes (means across fertilizer and year)									
		AWD	CF	AWD	CF	AWD	CF	AWD	CF
Mean	Mean	72.8	71.4	0.62	0.61	15.3	14.2	50	44
ANOVA (p values)									
Irrigation (I)		ns		ns		ns		ns	
Fertilizer (F)		*		ns		*		*	
Year (Y)		*		*		ns		ns	
I × F		ns		ns		ns		ns	
I × Y		ns		ns		ns		ns	
F × Y		ns		ns		ns		ns	
I × F × Y		ns		ns		ns		ns	

Tukey's honest significant difference (HSD) test indicates that the means denoted by the same lowercase letter or uppercase letter inside a column or row for the same response variable are not statistically different from one another at the 5 % level of probability. The abbreviations UDP, PU, VC, PL, and IPNS refer to the urea deep placement, prilled urea, vermicompost, poultry litter, and integrated plant nutrition system, respectively. * and ns indicate statistically significant and non-significant at the 5 % level of probability.

Table 9
The impacts of fertilizer, irrigation regimes and year on total nitrogen uptake (TNU), N harvest index (NHI), agronomic efficiency (AE_N) and recovery efficiency of N (RE_N) in the Boro season.

Fertilizer management	Year	TNU (kg ha^{-1})		NHI		AE_N (kg grain kg^{-1} N)		RE_N (%)	
		Mean of irrigation regimes		Mean of irrigation regimes		AWD	CF	Mean of irrigation regimes	
Fertilizer and irrigation regimes interaction									
Control-N0	Mean	32.9d		0.53b		–	–	–	
UDP-N78		97.5a		0.59a		44.8 aA	39.2 aA	83a	
PU-N78		75.0c		0.57 ab		30.7 cA	27.2 cB	54c	
PU-N104		92.9 ab		0.56 ab		28.5 cA	28.4 cA	58c	
IPNS-N78 (PU + VC)		76.1c		0.56 ab		32.3 cA	28.8bcA	55c	
IPNS-N78 (UDP + PL)		93.5a		0.57a		39.0bA	39.5 aA	78 ab	
IPNS-N78 (PU + PL)		88.3b		0.57 ab		39.7bA	33.2bB	71b	
Effects of the year (mean across fertilizer and irrigation regimes)									
Mean	2018	80.3a		0.56b		32.3b		66b	
	2019	74.9b		0.54b		34.6 ab		61b	
	2020	83.1a		0.60a		35.8a		73a	
Effects of irrigation regimes (means across fertilizer and year)									
		AWD	CF	AWD	CF	AWD	CF	AWD	CF
Mean	Mean	80.3	78.7	0.57	0.56	35.8A	32.7B	69A	64B
ANOVA (p values)									
Irrigation (I)		ns		ns		*		*	
Fertilizer (F)		*		*		*		*	
Year (Y)		*		*		*		*	
I × F		ns		ns		*		ns	
I × Y		ns		ns		ns		ns	
F × Y		ns		ns		ns		ns	
I × F × Y		ns		ns		ns		ns	

Tukey's honest significant difference (HSD) test indicates that the means denoted by the same lowercase letter or uppercase letter inside a column or row for the same response variable are not statistically different from one another at the 5 % level of probability. The abbreviations UDP, PU, VC, PL, and IPNS refer to the urea deep placement, prilled urea, vermicompost, poultry litter, and integrated plant nutrition system, respectively. * and ns indicate statistically significant and non-significant at the 5 % level of probability.

irrigation gave a higher rice yield and TDM over CF (Table 6). Although AWD irrigation could lead to enhanced N loss through leaching, nitrification, and subsequent denitrification, some reports have shown that it does not increase N loss due to the reduction in vertical NH_4^+-N and total N leaching [46,47]. In AWD irrigation, rice plants can get N from both NH_4^+ and NO_3^- synchronously as per demand due to the continuous wetting and drying [35,36,48]. However, across the irrigation regimes and fertilizer treatments, significantly higher yield and TDM were observed in AWD irrigation than in CF irrigation (Table 6). Because AWD irrigation increases the root-to-shoot ratio, root activity, and grain-filling rate and reduces panicle degeneration, it thus increases grain yield [18,49].

4.2. Nitrogen uptake and nitrogen use efficiency

Integrated use of poultry litter with UDP or PU significantly ($p < 0.05$) enhanced the agronomic efficiency and recovery efficiency of N compared to sole application of PU in Aus and Boro seasons (Tables 7 and 9). The higher AE_N and RE_N might be correlated with higher grain yield and total N uptake (Tables 4–9). Our findings are in line with the literature [8,17,23,30]. Organic inputs release nutrients slowly and steadily, which provides sufficient nutrients throughout the rice-growing season. Moreover, organic inputs reduce N leaching due to improvement in root morphology and physiological features, which could help the plant to take in nutrients from the soil more quickly and easily [23,50]. On the other hand, UDP alone increased TNU, AE_N, and RE_N compared to broadcast PU (Tables 7–9). UDP applied in subsurface soil increases the contact of fertilizer granules with clay particles of soil, reducing N loss as NH_3 volatilization, which could increase the TNU and NUE. Moreover, UDP improves root growth by providing more N in the rhizosphere compared to broadcasting urea [34,51]. UDP also ensures prolonged N availability and promotes biological N fixation throughout the rice-growing season due to most of the N being retained in the non-exchangeable NH_4^+ form in the reduced (anaerobic layer) zone [34,40]. Thus, the combined application of organic (PL) and inorganic (UDP) fertilizer improves TNU and NUE by providing additional C and N substrates. However, the incorporation of VC with PU as IPNS reduced TNU and NUE compared to the combined application of PU with PL in this study, which might be linked with lower rice yield (Table 9). With relatively slow mineralization of VC, the plant could suffer a nutrient shortage at the early stage of growth, reducing tiller and panicle production, thus resulting in lower yield.

There was a statistically significant ($p < 0.05$) relationship between irrigation regime and fertilizer treatment with AE_N, while the relationship with TNU and RE_N was insignificant in Boro season (Table 9). AWD irrigation increased AE_N compared to CF under PU with PL as an IPNS treatment, which could be associated with the increased rice yield (Table 6). Across fertilizer treatments and years, AWD irrigation increased AE_N and RE_N compared to CF conditions (Table 9). This is because AWD irrigation improves root morphology and physiology, which could help the plant take up more nutrients from soil. Moreover, this could increase the oxygen concentration in the rhizosphere soil, which would help maintain an appropriate NH_4^+/NO_3^- ratio, thus increasing TNU and NUE [29,31,33,52]. The findings of this study suggest that combining organic (PL) input and inorganic (UDP) fertilizers, and sole application of

UDP with AWD irrigation could be a promising alternative for enhancing rice yield and NUE while conserving irrigation water, with the added benefits of improved soil health and rice yield [7–9,26].

5. Conclusion

The combined application of organic inputs and inorganic fertilizer as an IPNS can increase rice yield, TDM, and NUE compared to broadcast PU. The effects were consistent across three seasons and three years. In both wet and dry seasons, the sole application of UDP increased rice yields, TDM, and NUE compared to PU at similar N rates. Compared to CF conditions, AWD irrigation increased rice yields, TDM, and NUE during Boro season across the years and fertilizer treatments. Under AWD irrigation, UDP alone or in combination with poultry litter as an IPNS resulted in a greater rice yield and TDM than CF. The findings imply that either a single application of UDP or a combined application of UDP with PL as an IPNS under AWD irrigation is agronomically sound, as this technique saves irrigation water while also improving soil health. Since our results are from a single location we suggest further study across different agro-ecological zones of Bangladesh to draw a comprehensive conclusion. In addition, the research was conducted using single rice varieties irrespective of seasons, it is necessary to conduct additional research utilizing several rice cultivars to determine how fertilizer affects different rice varieties across the country.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

S.M. Mofijul Islam: Conceptualization, Formal analysis, Investigation, Writing – original draft, Methodology, Writing – review & editing. **Yam Kanta Gaihre:** Formal analysis, Writing – review & editing, Conceptualization. **Md. Rafiqul Islam:** Investigation, Methodology, Supervision. **Aminul Islam:** Investigation, Methodology. **Upendra Singh:** Formal analysis, Methodology, Writing – review & editing. **Bjoern Ole Sander:** Conceptualization, Writing – review & editing, Writing – original draft.

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.

Acknowledgements

The Krishi Gobeshona Foundation (KGF), Bangladesh, provided financial support for this study. Y.K. Gaihre's time was co-funded by the Feed the Future Sustainable Opportunities for Improving Livelihoods with Soils (SOILS) Consortium (Cooperative Agreement No. AID-FRS-IO-15-00001). B.O. Sander's time was also co-funded by the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC) and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). We would like to thank Julie Kohler for providing editing services.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e23110.

References

[1] S. Hu, Y. Wang, L. Yang, Response of rice yield traits to elevated atmospheric CO_2 concentration and its interaction with cultivar, nitrogen application rate and temperature: a meta-analysis of 20 years FACE studies, Sci. Total Environ. 764 (2021), 142797, https://doi.org/10.1016/j.scitotenv.2020.142797.

[2] BBS, Year book of agricultural statistics, in: Bangladesh Bureau of Statistics, Statistics and Informatics Division, Ministry of Planning, Government of the People's Republic of Bangladesh, 32nd ed., 2020. www.bbs.gov.bd. (Accessed 17 August 2021).

[3] Y.K. Gaihre, et al., Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in Bangladesh, Geoderma 259–260 (2015) 370–379.

[4] Y.K. Gaihre, et al., Nitrous oxide and nitric oxide emissions and nitrogen use efficiency as affected by nitrogen placement in lowland rice fields, Nutr. Cycl. Agroecosyst. 110 (2018) 277–291.

[5] S.M.M. Islam, et al., Rice yields and nitrogen use efficiency with different fertilizers and water management under intensive lowland rice cropping systems in Bangladesh, Nutr. Cycl. Agroecosyst. 106 (2016) 143–156.

[6] S.M.M. Islam, et al., Nitrous oxide and nitric oxide emissions from lowland rice cultivation with urea deep placement and alternate wetting and drying irrigation, Sci. Rep. 8 (2018), 17623, https://doi.org/10.1038/s41598-018-35939-7.

[7] S.M.M. Islam, et al., Effects of water management on greenhouse gas emissions from farmers' rice fields in Bangladesh, Sci. Total Environ. 734 (2020), 139382, https://doi.org/10.1016/j.scitotenv.2020.139382.

[8] S.M.M. Islam, et al., Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management, J. Environ. Manag. 307 (2022), 114520, https://doi.org/10.1016/j.jenvman.2022.114520.

[9] S.M.M. Islam, et al., Integrated plant nutrient systems improve rice yields without affecting greenhouse gas emissions from lowland rice cultivation, Sustainability 14 (2022), 11338, https://doi.org/10.3390/su141811338307.
[10] R. Lal, Restoring soil quality to mitigate soil degradation, Sustainability 7 (2015) 5875–5895, https://doi.org/10.3390/su7055875.
[11] K. Akhtar, et al., Changes in soil enzymes, soil properties, and maize crop productivity under wheat straw mulching in Guanzhong, China, Soil Tillage Res. 182 (2018) 94–102.
[12] A. Cai, et al., Soil fertility and crop yield after manure addition to acidic soils in South China, Nutr. Cycl. Agroecosyst. 111 (2018) 1–12.
[13] A. Araújo, V. Santos, R. Monteiro, Responses of soil microbial biomass and activity for practices of organic and conventional farming systems in Piauí state, Brazil, Eur. J. Soil Boil. 44 (2008) 225–230.
[14] M. Qaswar, 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. 198 (2020) 1–6.
[15] Y. Lin, et al., Influence of poultry litter on crop productivity under different field conditions: a meta-analysis, Agron. J. 110 (2018) 807–818, https://doi.org/10.2134/agronj2017.09.0513.
[16] M.I.U. Sarkar, et al., 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. 4 (2019) 1–14, https://doi.org/10.9734/AJSSPN/2019/v4i430050.
[17] M.M. Rahman, et al., Integrated nutrient management enhances productivity and nitrogen use efficiency of crops in acidic and charland soils, Plants 10 (2021) 2547, https://doi.org/10.3390/plants10112547.
[18] J. Liu, et al., Long-term organic fertilizer substitution increases rice yield by improving soil properties and regulating soil bacteria, Geoderma 404 (2021), https://doi.org/10.1016/j.geoderma.2021.115287.
[19] D. Sihi, et al., Evaluation of soil health in organic vs. conventional farming of basmati rice in North India, J. Plant Nutr. Soil Sci. 180 (2017) 389–406.
[20] S. Bei, et al., Response of the soil microbial community to different fertilizer inputs in a wheat-maize rotation on a calcareous soil, Agric. Ecosyst. Environ. 260 (2018) 58–69.
[21] S. Yadvinder, et al., Poultry litter as a nitrogen and phosphorous source for the rice–wheat cropping system, Biol. Fertil. Soils 45 (2009) 701–710, https://doi.org/10.1007/s00374-009-0373-z.
[22] A.D. Samuel, et al., Effects of long term application of organic and mineral fertilizers on soil enzymes, Revista De Chimie 69 (2018) 2608–2612, https://doi.org/10.37358/RC.18.10.6590.
[23] A. Iqbal, et al., Organic manure coupled with inorganic fertilizer: an approach for the sustainable production of rice by improving soil properties and nitrogen use efficiency, Agronomy 9 (2019) 651, https://doi.org/10.3390/agronomy9100651.
[24] M. Ishaque, et al., Long-term integrated nutrient management for rice-based cropping pattern: effect on growth, yield, nutrient uptake, nutrient balance sheet, and soil fertility, Commun. Soil Sci. Plant Anal. 38 (2007) 579–610, https://doi.org/10.1080/00103620701215718.
[25] T. Shankar, et al., Influence of integrated nutrient management on growth and yield attributes of summer rice (Oryza sativa L.), Crop Res 55 (2020) 1–5, https://doi.org/10.31830/2454-1761.2020.001.
[26] R.M. Lampayan, et al., Adoption and economics of alternate wetting and drying water management for irrigated lowland rice, Field Crops Res. 170 (2015) 95–108.
[27] S.F. Islam, et al., Reducing greenhouse gas emissions and grain arsenic and lead levels without compromising yield in organically produced rice, Agric. Ecosyst. Environ. 295 (2020), https://doi.org/10.1016/j.agee.2020.106922.
[28] B.A.M. Bouman, et al., Yield and water use of irrigated tropical aerobic rice systems, Agric. Water Manage. 74 (2005) 87–105.
[29] L. Liu, et al., 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. 154 (2013) 226–235.
[30] S.M.M. Islam, et al., 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. 196 (2018) 144–153, https://doi.org/10.1016/j.agwat.2017.11.002.
[31] Z. Wang, et al., Grain yield, water and nitrogen use efficiencies of rice as influenced by irrigation regimes and their interaction with nitrogen rates, Field Crops Res. 193 (2016) 54–69.
[32] V.H. Trang, et al., Institutional analysis for scaling alternate wetting and drying for low-emissions rice production: evidence from Bangladesh, Clim. Dev. (2022), https://doi.org/10.1080/17565529.2022.2036088.
[33] L. Xue, Y. Yu, L. Yang, Maintaining yields and reducing nitrogen loss in rice-wheat rotation system in Taihu Lake region with proper fertilizer management, Environ. Res. Lett. 9 (2014), 115010, https://doi.org/10.1088/1748-9326/9/11/115010.
[34] T.Q. Liu, et al., Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China, Field Crops Res. 184 (2015) 80–90.
[35] Y. Zhang, et al., Integrated management approaches enabling sustainable rice production under alternate wetting and drying irrigation, Agric. Water Manag. 281 (2023), 108265, https://doi.org/10.1016/j.agwat.2023.108265.
[36] N.M. Dong, et al., Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Vietnam, Soil Biol. Biochem. 47 (2012) 166–174.
[37] S. Yoshida, et al., Laboratory Manual for Physiological Studies of Rice, third ed., International Rice Research Institute, Manila, Philippines, 1976.
[38] U. Singh, et al., Nitrogen dynamics and crop growth on an alfisol and a vertisol under rainfed lowland rice-based cropping system, Field Crops Res. 61 (1999) 237–252.
[39] K.A. Gomez, A.A. Gomez, Statistical Procedure for Agricultural Research, second ed., John Willey and Sons, Singapore, 1984, pp. 28–192.
[40] N.K. Savant, P.J. Stangel, Deep placement of urea supergranules in transplanted rice: principles and practices, Fertil. Res. 25 (1990) 1–83.
[41] V. Kapoor, et al., Rice growth, grain yield, and floodwater nutrient dynamics as affected by nutrient placement method and rate, Agron. J. 100 (2008) 526–536.
[42] D. Neina, The role of soil pH in plant nutrition and soil remediation, Appl. Environ. Soil Sci. (2019), 5794869, https://doi.org/10.1155/2019/5794869.
[43] M. Navas, Effect of five forage legume covers on soil quality at the Eastern plains of Venezuela, Appl. Soil Ecol. 49 (2011) 242–249.
[44] Y.P. Singh, et al., Plant and soil responses to the combined application of organic amendments and inorganic fertilizers in degraded sodic soils of Indo-Gangetic Plains, Commun. Soil Plant Anal. 50 (2019) 2640–2654, https://doi.org/10.1080/00103624.2019.1671446.
[45] S. Das, et al., Effect of deep placement of nitrogen fertilizers on rice yield and N use efficiency under water regimes, SAARC J. Agri. 13 (2015) 161–172.
[46] H. Zhang, et al., An alternate wetting and moderate soil drying regime improves root and shoot growth in rice, Crop Sci. 49 (2009) 2246–2260.
[47] X.T. Wang, et al., Recovery of N labeled urea and soil nitrogen dynamics as affected by irrigation management and nitrogen application rate in a double rice cropping system, Plant Soil 343 (2011) 195–208.
[48] Y. Sun, et al., The effects of different water and nitrogen managements on yield and nitrogen use efficiency in hybrid rice of China, Field Crops Res. 127 (2012) 85–98.
[49] G.W. Xu, D.K. Lu, H.Z. Wang, Y. Li, Morphological and physiological traits of rice roots and their relationships to yield and nitrogen utilization as influenced by irrigation regime and nitrogen rate, Agric. Water Manag. 203 (2018) 385–394, https://doi.org/10.1016/j.agwat.2018.02.033.
[50] W. Wu, S. Cheng, Root genetic research, an opportunity and challenge to rice improvement, Field Crops Res. 165 (2014) 111–124.
[51] S. Liu, et al., Optimizing nitrogen application depth can improve crop yield and nitrogen uptake – a global meta-analysis, Field Crop Res 295 (2023), 108895, https://doi.org/10.1016/j.fcr.2023.108895.
[52] J. Yang, Q. Zhou, J. Zhang, Moderate wetting and drying increases rice yield and reduces water use, grain arsenic level, and methane emission, Crop J 151–158 (2017), https://doi.org/10.1016/j.cj.2016.06.002.