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Effects of integrated nutrient management and urea deep placement on rice yield, nitrogen use efficiency, farm profits and greenhouse gas emissions in saline soils of Bangladesh

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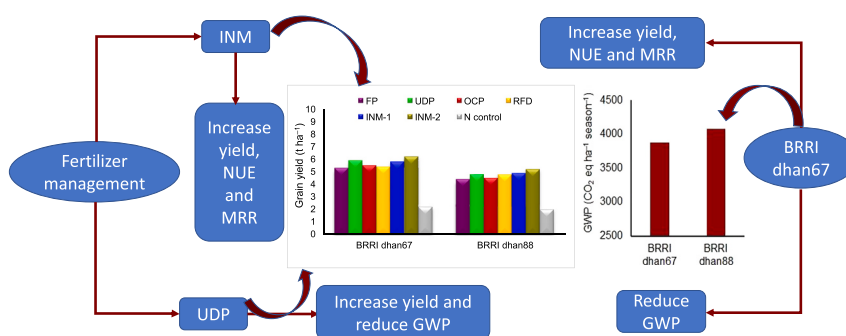
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HIGHLIGHTS

- Integrated nutrient management (INM) reduced soil salinity, increased rice yield, and marginal rate of return.
- BRRI dhan67, a saline-tolerant cultivar, significantly increased rice yield by 52 % than BRRI dhan88 in farmers' fields.
- Urea deep placement significantly reduced GWP without causing yield loss.
- BRRI dhan67 significantly reduced yield scaled CH₄ emissions by 22 % compared to BRRI dhan88.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil salinity is one of the major yield-limiting factors in the coastal ecosystems of Bangladesh. An efficient fertilizer management practice and selection of appropriate crop cultivars could play a crucial role in improving yield and promoting low-carbon agriculture across saline soils. A two-year multi-location field experiment was conducted during the Boro (dry) season (December–April) to investigate the effects of fertilizer management and rice cultivar selection on rice yield, economic viability, and global warming potential (GWP) in coastal saline soils of Bangladesh. The study included seven fertilizer treatments with varying nitrogen rates and sources, as well as two rice cultivars (BRRI dhan67 and BRRI dhan88). The results showed that integrated nutrient management-2 (INM-2) significantly ($p < 0.05$) increased rice yield and nitrogen use efficiency compared to other treatments for both BRRI dhan67 and BRRI dhan88. Similarly, INM-2 gave a higher return on fertilizer investment and marginal benefit-cost ratio than other treatments in both locations and under both cultivars.

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BRRRI dhan67 significantly ($p < 0.05$) increased rice yield relative to BRRRI dhan88 by 21 % and 52 % at the BRRRI farm and Kaliganj in Satkhira, respectively. The cost-dominant analysis excluded BRRRI dhan88 and all fertilizer treatments, except urea deep placement (UDP) and INM-2, from consideration in both locations. Consequently, INM-2 and UDP proved to be economically viable in both locations, with INM showing a higher marginal rate of return than UDP in BRRRI dhan67. In terms of environmental sustainability, UDP significantly ($p < 0.05$) reduced GWP and yield-scaled emissions of CH_4 by 31 % and 38 % without causing yield loss compared to INM-2. Similarly, BRRRI dhan67 significantly ($p < 0.05$) reduced GWP and yield-scaled emissions of CH_4 by 5 and 22 % compared to BRRRI dhan88. These findings suggest that selecting salt-tolerant rice cultivars and implementing appropriate fertilizer management practices can enhance economic profitability, ensure food security, and mitigate the adverse effects of climate change in coastal saline soils.

1. Introduction

Soil salinity is one of the major challenges to sustainable crop production in coastal regions (Rahman et al., 2018). Increasing soil salinity is associated with rising sea levels and seawater intrusion, which is directly affected by climate change (Cassia et al., 2018). The salinity level further increases with the increased temperature once evapotranspiration exceeds rainfall and/or irrigation. Salinity affects both crop productivity and soil health. Worldwide, soil salinity is one of the major environmental factors contributing to a severe loss of crop yield due to the changes in plant-water relations, ion concentrations, and ratios of ions in plant tissues (Islam et al., 2022a).

The coastal regions in the world, many of which are significant crop production locations, are more vulnerable due to their low elevation and shallow saline groundwater, which causes soil salinization (van der Zee et al., 2017). Soil salinity is a serious constraint to crop productivity in the coastal area of Bangladesh (Rahman et al., 2020). This area covers >30 % of the country's cultivable land, and 63 % of this coastal area is affected by various degrees of salinity and reduced potential of agriculture (SRDI, 2010). Cropping intensity in this area is low relative to the other parts of Bangladesh due to a shallow saline water table, a lack of fresh irrigation water in the Rabi/Boro (dry) season, poor drainage facilities, improper soil management, and unavailability of salt-tolerant cultivars (Bell et al., 2019). In addition, delays in establishing rabi crops due to excess water at the end of the Aman (wet) season decrease the crop yield and increase the risk of crop damage caused by high salinity and pre-monsoon rainfall (Islam et al., 2022b). Furthermore, farmers cannot cultivate Boro rice due to the scarcity of fresh irrigation water in this season. Therefore, most farmers leave the land fallow in the dry season and cultivate only Aman rice in the wet season.

In the coastal area, the groundwater table is shallow (Islam et al., 2022b), and the soil salinity varies seasonally (SRDI, 2010); thus, soils are not supported for sustainable crop production. However, different approaches and strategies are available to cope with agriculture production in saline soil. For example, using salt-tolerant cultivars is one of the most effective approaches to combat salinity. Similarly, drainage (surface or subsoil) is another effective way to alleviate salinity (Islam et al., 2022b). Leaching is the most common method to reclaim saline soil, in which non-saline or slightly saline water and gypsum are applied to the soil surface to leach the salt level (Ghafoor et al., 2012; Shaygan and Baumgartl, 2022). In addition, using organic matter amendment is another important way to improve plant growth in saline soil, as it enhances salt leaching and improves soil quality, i.e., physical, chemical, and biological (Walker and Bernal, 2008; Mao et al., 2022).

However, all methods may not be suitable, sustainable, and environmentally friendly for all regions worldwide. For example, all salt-tolerant genotypes may not perform equally across different regions and may not be profitable to farmers. Drainage, particularly subsoil drainage, may not be suitable for poor and smallholder farmers as it is expensive and may not be environmentally friendly due to the chance of polluting water (Islam et al., 2022b). Salt leaching through chemical amendment (gypsum) may not be effective in heavy textured soil (Shaygan and Baumgartl, 2022), and subsurface drains may require achieving effective leaching.

Saline soils contain excess neutral soluble salts, which interfere with the normal nutrition of crops (e.g., Na against K and phosphate against chloride). Salinity also interferes with the activities of the soil's microbial population and thus hamper the plant nutrient transformation (e.g., decreased nitrification rate). Therefore, proper fertilizer management, which is readily available to farmers, affordable (cheap), profitable, and sustainable approach, is needed to increase crop yield and improve farmers' livelihood in the coastal saline area. In addition, the inefficient and imbalanced use of nitrogen (N) fertilizer could increase environmental pollution due to increased greenhouse gas emissions. Previous studies have reported that urea deep placement (UDP) and/or integrated nutrient management (INM) combining inorganic and organic manure could be effective in increasing crop yield without increasing greenhouse gas emissions (Islam et al., 2020; Ding et al., 2022). In addition to fertilizer management, selection of appropriate rice cultivars could reduce greenhouse gas emissions due to more robust root systems, which allow more O_2 in the rhizosphere and enhance CH_4 oxidation by the methanotrophs (Chen et al., 2019; Ding et al., 2022).

To the best of our knowledge, there are no studies conducted across saline soils in Bangladesh to determine the effects of UDP and INM compared to government soil test-based fertilizer recommendations or farmers' practices on greenhouse gas emissions, N use efficiency, and profitability of rice cultivars. Therefore, the present study was undertaken to find suitable fertilizer management and rice cultivars for increasing rice yield and economic viability and mitigating greenhouse gas emissions and soil salinity in the coastal saline region of Bangladesh. This study hypothesized that compared to other treatments, INM and UDP in combination with salt-tolerant rice cultivars would be a suitable technique for reducing soil salinity and greenhouse gas emissions, increasing rice yield, and improving farmers' livelihood in the coastal areas of Bangladesh.

2. Materials and methods

2.1. Experimental site and weather conditions

The field experiments were conducted in two locations of Satkhira district, one in the Bangladesh Rice Research Institute (BRRRI) farm (latitude: 22°45'11" N, longitude: 89°6'24" E), Satkhira Sadar, and another in the farmers' field, Kaliganj (latitude: 22°24'41" N, longitude: 89°6'32" E), during Boro seasons 2019–20 and 2020–21. Boro rice is cultivated during the dry season; thus, its cultivation completely depends on irrigation. Bangladesh has a humid sub-tropical monsoon climate and experiences average annual rainfall and temperature of about 2000 mm and 25 °C, respectively. Daily mean temperature and rainfall data of the experimental period are illustrated in Fig. S1. The physicochemical properties of soil are shown in Table 1.

2.2. Experimental design and treatments

Experimental treatments consist of seven fertilizer treatments (main plots) and two rice cultivars (sub-plots). Fertilizer treatments were a combination of organic and inorganic sources, including i) farmers' practice (FP) at 138 kg N ha⁻¹; (ii) deep placement of urea briquette

Table 1
Physicochemical properties of initial soil.

Soil properties	BRRi farm, Satkhira	Kaliganj, Satkhira	Analysis method
pH _{1:2.5}	7.83	7.73	Glass electrode
EC _e (dS m ⁻¹)	5.32	7.15	Saturation paste extract
Organic carbon (%)	1.89	0.76	Wet oxidation
Total N (%)	0.20	0.15	Kjeldahl
Available P (mg kg ⁻¹)	21.93	19.53	0.5 M NaHCO ₃ extraction
Available K (cmol kg ⁻¹)	0.63	0.58	Neutral 1.0 N NH ₄ OAc extraction
Available Na (mg kg ⁻¹)	1.22	0.52	CH ₃ COONH ₄ extraction
Available Ca (cmol kg ⁻¹)	15.08	17.83	CH ₃ COONH ₄ extraction
Available Mg (cmol kg ⁻¹)	5.56	5.46	CH ₃ COONH ₄ extraction
Available S (mg kg ⁻¹)	24.09	7.12	Ca(H ₂ PO ₄) ₂ extraction
Available Zn (mg kg ⁻¹)	1.5	0.87	DTPA extraction
Available Mn (mg kg ⁻¹)	34.09	28.86	DTPA extraction
CEC (meq/100 g soil)	22.48	24.39	–
SAR	0.38	0.15	–
Texture	Silty clay loam	Silty clay loam	Hydrometer method

(hereafter called urea deep placement: UDP) at 78 kg N ha⁻¹; (iii) Office Chérifien des Phosphates (OCP) fertilizer (9.4 % N, 20 % P, 5 % S, and 1 % Zn) at 110 kg N ha⁻¹; (iv) recommended fertilizer dose (RFD) fertilizer at 120 kg N ha⁻¹; (v) integrated nutrient management-1 (INM-1), consisting 100 % RFD and ash at 2 t ha⁻¹; (vi) integrated nutrient management-2 (INM-2), consisting of 70 % RFD with cow dung and ash at 2 t ha⁻¹; (vii) N control at 0 kg N ha⁻¹. The detail of treatments is presented in (Table 2). Among the seven treatments, FP, UDP, RFD, and both INM treatments were considered for the CH₄ and N₂O gas measurements. A split-plot design with three replications was used to lay out the treatment combinations. For the UDP treatment, a 2.7-g urea briquette (compressed prilled urea) was manually placed 8–10 cm below the soil surface at the center of four rice hills after ten days of transplanting. A 2.7-g urea briquette with a single application provided 78 kg N ha⁻¹ considering spacing 40 cm × 40 cm (62,500 briquettes per ha). The size of the experimental plot was 5 m × 6 m.

2.3. Crop management

Two to three rice seedlings per hill of BRRi dhan67 and BRRi dhan88 were transplanted at 20 × 20 cm spacing. BRRi dhan67 can tolerate

Table 2
Treatment description of different fertilizer sources used in this experiment.

Treatments	Description	Nutrients from chemical fertilizer (kg ha ⁻¹)					Nutrients from OCP and organic fertilizer (kg ha ⁻¹)					Total nutrient (kg ha ⁻¹)				
		N	P	K	S	Zn	N	P	K	S	Zn	N ^a	P	K	S	Zn
FP	Farmers' practice	138	30	55	15	1.0	0	0	0	0	0	138	30	55	15	1.0
UDP ^b	Urea deep placement	78	20	70	18	2.5	0	0	0	0	78	20	70	18	2.5	
OCP fertilizer	OCP compound fertilizer	110	0	70	18	2.5	10.3	22.0	0	5.5	1.1	120	22	70	24	3.6
RFD	Recommended fertilizer dose	120	20	70	18	2.5	0	0	0	0	120	20	70	18	2.5	
INM-1 (100 % RFD + ash)	Integrated nutrient management-1 (100 % RFD + 2-ton ash ha ⁻¹)	120	20	70	18	2.5	0	5.0	25.4	1.2	0	120	25	95	19	2.5
INM-2 (70 % of RFD with ash + cow dung) ^c	INM-2 (70 % RFD with 2-ton ash +2-ton cow dung per ha)	84	14	56	13	1.7	22.0	18.6	42.4	5.0	0	106	33	98	18	1.7
N control	N control	0	20	70	18	2.5	0	0	0	0	0	0	20	70	18	2.5

^a Nitrogen use efficiency was calculated based on the total N rate.

^b This rate was used according to Islam et al. (2016).

^c This rate was fixed based on a previous study (Farid et al., 2011).

12–14 dS m⁻¹ (ECe) at the seedling stage and about eight dS m⁻¹ (ECe) at the vegetative to reproductive phase. The average growth duration and yield of BRRi dhan67 are about 145 days and 6.0 t ha⁻¹, respectively. In contrast, BRRi dhan88 is a salt susceptible cultivar whose average growth duration and yield are 142 days and 7.0 t ha⁻¹, respectively. Major crop management practices, such as weed and pest management, were maintained per BRRi's recommendations. Experimental plots were irrigated with shallow tube well water (2–4 dS/m). Triple super phosphate, muriate of potash, gypsum, and zinc sulphate were applied as basal during final land preparation. Urea fertilizers were used as three equal splits 8–10 days after transplanting, at maximum tillering and panicle initiation stages in all treatments except the N control and UDP treatments. Detailed fertilizer rates from different sources are presented in Table 2.

For the INM treatments, well-decomposed cow dung (1.11 % N, 0.68 % P, and 0.85 % K) and rice husk ash (0.25 % P and 1.27 % K) were applied during final land preparation. During the final land preparation, Office Chérifien des Phosphates (OCP) fertilizer was applied. Nutrient contents from organic fertilizer were adjusted with chemical fertilizer to calculate nitrogen use efficiency.

2.4. Soil salinity measurement

Three soil samples from each plot/sub-plot at 0–15 cm were collected, and then three samples were blended to make a composite sample. Soils were sampled at ten days intervals throughout the cropping season. The electrical conductivity (EC_e) of soil was estimated from saturated soil paste extract (Rhoades, 1996) using an EC meter (HI 993310, HANNA model).

2.5. Rice yield and grain and straw N content

Ten rice hills were randomly selected to determine tillers, effective tillers, grains per panicle, and 1000-grain weight. Rice plants were collected at soil level from 125 hills or 5 square meters of the center of each plot for grain and straw yield. The straw weight of 125 hills was taken, along with sub-samples, and the straw sub-samples were subsequently kept at 70 °C for 72 h. The straw yield was then calculated on an oven-dry basis. After being winnowed, the grains were sun-dried. The yield of rice was calculated and translated to t ha⁻¹ at 14 % moisture content. The micro Kjeldahl method was used to determine the N content of grain and straw (Yoshida et al., 1976).

2.6. Nitrogen use efficiency

Nitrogen use efficiency was computed according to Fageria and Barbosa (2001).

Agronomic efficiency of applied N (AE_N): It is expressed as kg grain

kg⁻¹ N.

$$AE_N = \frac{(G_f - G_c)}{N_t}$$

Where,

G_f is the grain yield of the fertilized plot (kg ha⁻¹)

G_c is the grain yield of the N control plot (kg ha⁻¹)

N_t is the rate of applied N (kg ha⁻¹)

Apparent recovery efficiency of applied N (ARE_N): It is expressed as a percentage.

$$ARE_N = \frac{(U_f - U_c)}{N_t} \times 100$$

Where,

U_f is the total plant uptake in the fertilized plot (kg ha⁻¹)

U_c is the total plant uptake in the N control plot (kg ha⁻¹)

N_t is the rate of applied N (kg ha⁻¹)

Physiological efficiency of applied N (PE_N): It is expressed as kg grain kg⁻¹ N uptake.

$$PE_N = \frac{G_f - G_c}{U_f - U_c}$$

Where,

G_f is the grain yield of the fertilized plot (kg ha⁻¹)

G_c is the grain yield of the N control plot (kg ha⁻¹)

U_f is the total N uptake of the fertilized plot (kg ha⁻¹)

U_c is the total N uptake of the control plot (kg ha⁻¹)

2.7. Gas sampling, analysis, and calculation of CH₄ and N₂O emissions

A detailed gas sampling method was described earlier by Islam et al. (2020). In brief, CH₄ and N₂O gas samples were taken using the closed chamber technique. Each chamber had a base (70 L) and a top (100 L). Each chamber base, considering six rice hills, was placed in the rice field by inserting it at 8–10 cm soil depth and was left there throughout the crop growth period. Each chamber consisted of a battery-powered fan and a thermometer. Gas samples were taken every seven days intervals using a 50 mL airtight syringe. Three gas samples were taken at 15-minute intervals during each sampling period. Gas samples were collected in 30-mL air-evacuated glass vials sealed with a butyl rubber septum for laboratory analysis.

CH₄ and N₂O gas concentration was measured using gas chromatography (Shimadzu GC-2014, Japan) equipped with a flame ionization detector (FID) and electron capture detector (ECD). The slope of the linear regression curves of gas concentration versus chamber closure time was used to calculate CH₄ and N₂O emission rates (Islam et al., 2020).

The following equation was used to compute the GWP of CH₄ and N₂O:

$$GWP \text{ (kg CO}_2 \text{ equivalent ha}^{-1}\text{)} = (TCH_4 \times 27 + TN_2O \times 273)$$

Where, TCH₄ is the total amount of CH₄ emission (kg ha⁻¹), TN₂O is the total amount of N₂O emissions (kg ha⁻¹), 27 and 273 are the GWP values for CH₄ and N₂O, respectively, to CO₂ over 100-year time horizon (IPCC, 2021).

The following equation was used to measure yield-scaled emission of CH₄ (kg t⁻¹ grain yield):

$$\text{Yield-scaled emissions} = \frac{\text{Cumulative CH}_4 \text{ emissions}}{\text{Yield}}$$

The emission factor of CH₄ (kg ha⁻¹ d⁻¹) and N₂O (g ha⁻¹ d⁻¹) was determined using the following equation:

$$\text{Emission factor} = \frac{\text{Cumulative CH}_4 \text{ or N}_2\text{O emissions}}{\text{Active growth periods}}$$

2.8. Economic analysis

Partial budget analysis was done to determine gross return, gross margin, returns on fertilizer investment, and marginal benefit-cost ratio compared to the N control. The supplementary file provides detailed information on the estimation procedures.

However, the marginal rate of return was calculated subject to the control treatment and based on the dominance analysis across the cultivars, which were calculated as follows:

$$\text{Marginal rate of return} = \frac{\text{Marginal gross margin of a treatment}}{\text{Marginal cost of the treatment}} \times 100$$

2.9. Risk analysis

To assess the economic viability, a stochastic simulation was constructed to evaluate the consequences of externalities and market uncertainties in rice farming (Anderson and Dillon, 1977; Hardaker et al., 2004; Chavas et al., 2010; Sarkar et al., 2022). In this study, the @RISK Program, integrated with Microsoft Excel and employing Monte-Carlo simulation, was utilized to simulate the risk-return trade-off associated with seven fertilizer treatments in saline ecosystems for two rice varieties, namely BRRI dhan67 and BRRI dhan88. The simulation adopted a triangular probability distribution and generated cumulative probability distribution functions to evaluate the gross margin of experimental plots (Hardaker et al., 2004). Moreover, the study incorporated the distribution of yield and price using the best, typical, and worst experimental yields, as well as the maximum, most likely, and lowest prices for two different rice varieties. A total of 10,000 iterations were performed during the simulation to ensure the stability of the risk and return trade-off distribution (Lien, 2003).

2.10. Data analysis

Data on rice yield and yield contributing characters, nitrogen use efficiency, greenhouse gas emissions, emission factors, global warming potential, and yield-scaled emission were analyzed using the STAR 2.0.1 program developed by the International Rice Research Institute, Philippines. A split-plot design was employed for the analysis, utilizing Analysis of Variance (ANOVA), with fertilizer treatments as the main plot and cultivars as the sub-plots. The data from multiple years were combined for the analysis. Tukey's honest significant difference (HSD) test was considered to separate the treatment means at the 5 % probability level.

3. Results

3.1. Dynamics of soil salinity

Soil salinity was measured from seven fertilizer treatments throughout the rice-growing seasons at BRRI farm and Kaliganj in Satkhira (Fig. 1). Soil salinity showed a linear increase over time, reaching its peak after forty days of transplanting. However, the integrated nutrient management (INM) treatments demonstrated a reduction in soil salinity compared to other treatments in both locations. The levels of soil salinity were higher in Kaliganj compared to the BRRI farm in Satkhira. In 2020, there was a slight decrease in soil salinity from 55 to 66 days due to rainfall at both the BRRI farm and Kaliganj in Satkhira. Throughout the year, soil salinity ranged from 3.1 to 7.7 dS m⁻¹ in Kaliganj, while it varied from 1.9 to 5.5 dS m⁻¹ at the BRRI farm in Satkhira (Fig. 1).

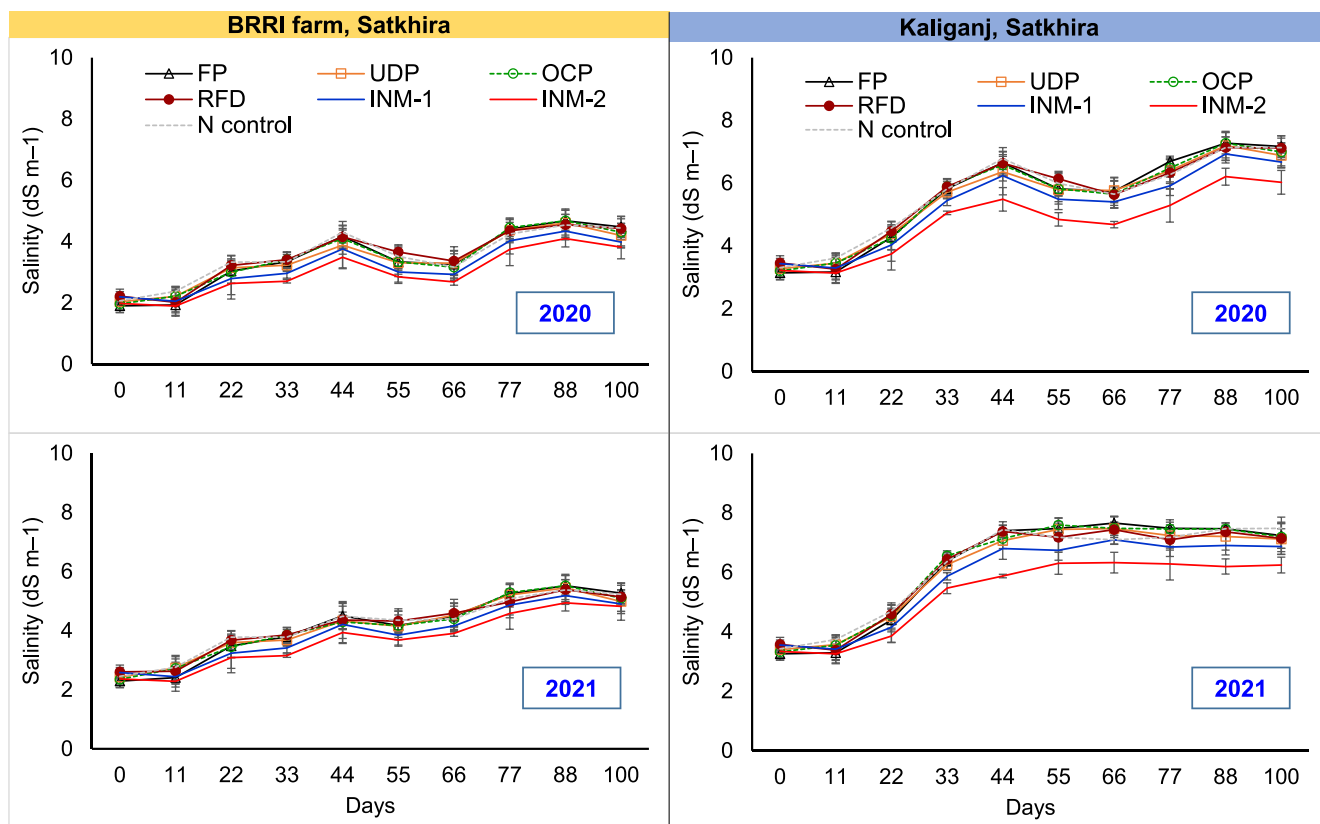


Fig. 1. Dynamics of soil salinity in different fertilizer management during the Boro seasons. FP, UDP, RFD, and INM correspond to farmers' practice, urea deep placement, recommended fertilizer dose, and integrated nutrient management. Error bar indicates standard error of the mean ($n = 3$).

Table 3

Grain yield, straw yield, total nitrogen uptake (TNU), agronomic efficiency of N (AE_N), recovery efficiency of N (RE_N), and physiological efficiency of N (PE_N) of Boro rice as influenced by fertilizer management, rice variety and year, and their interaction at BRRRI farm, Satkhira.

Fertilizer treatment	Year	Grain yield (t ha ⁻¹)		Straw yield (t ha ⁻¹)		TNU (kg ha ⁻¹)		AE _N (kg grain kg ⁻¹ N)		RE _N (%)		PE _N (kg grain kg ⁻¹ N uptake)
		V1	V2	V1	V2	V1	V2	V1	V2	V1	V2	Mean of 2 cultivars
Effects of fertilizer treatment (means across year and variety)												
FP	Mean	5.3cA	4.4bB	5.4b	4.4a	82.4b	69.7b	21.9d	18.0d	39.7d	31.6d	56.1b
UDP		5.9abA	4.8abB	6.2a	4.8a	82.0b	70.8b	47.2a	36.9a	69.8a	57.4a	66.0a
OCP fertilizer		5.5bcA	4.5bB	5.7ab	4.5a	92.7a	71.2b	27.6c	21.3cd	54.3c	37.6cd	53.6b
RFD		5.4bcA	4.8abB	5.4b	4.6a	83.4b	72.6ab	26.3cd	23.3c	46.5d	38.8cd	59.0ab
INM-1 (100 % RFD + ash)		5.8abA	4.9abB	5.8ab	4.8a	96.8a	80.4a	29.8c	24.3c	57.7bc	45.2bc	52.5b
INM-2 (70 % RFD with ash + cow dung)		6.2aA	5.2aB	6.1a	5.0a	94.3a	81.0a	37.7b	30.1b	63.0ab	48.8b	58.7ab
N control		2.2dA	2.0cA	2.3c	2.0b	27.5c	26.1c	-	-	-	-	-
Effects of the year (means across variety and fertilizer treatment)												
Mean		V1	V2	Mean of 2 cultivars	V1	V2	V1	V2	V1	V2	Mean of 2 cultivars	
	2020	5.6a	5.0a	5.2a	84.7a	77.5a	32.9a	29.6a	56.4a	49.4a	58.7a	
	2021	4.8b	3.7b	4.4b	74.9b	57.3b	30.5b	21.7b	53.9a	38.1b	56.6a	
Effects of variety (means across year and fertilizer treatment)												
Mean	Mean	5.2A	4.4B	5.3A	4.3B	79.8A	67.4B	31.7A	25.7B	55.2A	43.7B	57.1A 58.2A
ANOVA (p values)												
Fertilizer (F)		*		*	*	*	*	*	*	*	*	*
Variety (V)		*		*	*	*	*	*	*	*	*	ns
Year (Y)		*		*	*	*	*	ns	*	*	*	ns
F × V		*		*	*	*	*	*	*	*	*	ns
F × Y		*		ns	*	*	*	ns	*	ns	*	ns
V × Y		*		*	*	*	*	*	*	*	*	ns
F × V × Y		ns		ns	ns	ns	ns	ns	ns	ns	ns	ns

For each response variable, means followed by the identical uppercase letters in a row and lowercase letters in a column do not differ significantly at a 5 % level of probability. FP, UDP, RFD, INM, V1, and V2 correspond to farmers' practice, urea deep placement, recommended fertilizer dose, integrated nutrient management, BRRRI dhan67, and BRRRI dhan88, respectively. * and ns denote significant, and non-significant at a 5 % level of probability, respectively.

3.2. Yield contributing characters

The interaction effect between fertilizer management and cultivar on the tiller, panicle, unfilled-grain, filled-grain, grain per panicle, and 1000-grain weight was insignificant in both locations of BRRI farm (Table S1) and Kaliganj (Table S2) in Satkhira. The higher tiller (13–16 %) and panicle (13–19 %) production were observed in integrated nutrient management-2 (INM-2) treatment (70 % recommended fertilizer dose (RFD) with ash and cow dung) compared to farmers' practice (FP), Office Chérifien des Phosphates (OCP) fertilizer, and RFD treatments at BRRI farm, while in Kaliganj, higher tiller (7–79 %) and panicle (6–78 %) were found in INM-2 compared to all other treatments. Similarly, a greater filled grain was found in INM-2 compared to FP and RFD treatments in both locations. Except for the control treatment, no significant variations were observed in the grain per panicle among the other treatments. Similarly, there was no significant variation in the 1000-grain weight across the treatments in both locations. However, BRRI dhan67 showed significant improvements ($p < 0.05$) in tiller (6 %), panicle (6 %), filled-grain (15 %), grain per panicle (10 %), and 1000-grain weight (5 %) in BRRI farm, while in Kaliganj, it gave higher tiller (9 %), panicle (10 %), filled-grain (24 %), grain per panicle (13 %), and 1000-grain weight (5 %) compared to BRRI dhan88. Additionally, BRRI dhan67 gave a lower percentage of unfilled grains than BRRI dhan88 in both locations.

3.3. Rice yield

The fertilizer treatments displayed a significant ($p < 0.05$) interaction effect with cultivars on grain and straw yield in both locations (Tables 3 and 4). At the BRRI farm, the application of integrated nutrient management-2 (INM-2) gave higher grain yield by 13–17 % in BRRI dhan67 and 8–18 % in BRRI dhan88 relative to farmers' practice (FP),

Office Chérifien des Phosphates (OCP) fertilizer, and recommended fertilizer dose (RFD) treatments. Similarly, INM-2 produced a higher straw yield than FP and RFD treatments for BRRI dhan67, while no significant variation in straw yield was observed for BRRI dhan88. However, across the fertilizer treatments, BRRI dhan67 produced a significantly ($p < 0.05$) higher grain and straw yield by 10 % and 15 %, respectively, compared to BRRI dhan88 (Table 3).

In Kaliganj, a higher grain yield (13 %) was observed in INM-2 compared to FP and INM-1 treatments under BRRI dhan67. Similarly, a higher grain yield (17–26 %) was observed in INM-2 compared to FP and RFD treatments (Table 4). As in grain yield, the higher straw yield was found in INM-1 than in FP. Across the fertilizer treatments, BRRI dhan67 gave a significant ($p < 0.05$) increase in grain and straw yield by 18 % and 17 %, respectively, compared to BRRI dhan88 in Kaliganj, Satkhira (Table 4).

3.4. Total nitrogen uptake and nitrogen use efficiency

The interaction between fertilizer management and cultivars had a significant ($p < 0.05$) effect on total nitrogen uptake, agronomic efficiency of N (AE_N), and recovery efficiency of N (RE_N). However, it was found insignificant for the physiological efficiency of N (PE_N) under both locations (Tables 3 and 4). At the BRRI farm, both integrated nutrient management (INM) treatments gave higher total nitrogen uptake relative to other treatments for both BRRI dhan67 and BRRI dhan88 (Table 3). Urea deep placement (UDP) and INM-2 treatments showed similar RE_N and PE_N . However, UDP significantly ($p < 0.05$) increased AE_N by 25–116 % in BRRI dhan67 and 23–105 % in BRRI dhan88 compared to other treatments. In Kaliganj, INM-2 resulted in higher total nitrogen uptake by 26 % in BRRI dhan67 and 21 % in BRRI dhan88 compared to farmers' practice (FP) (Table 4). The highest AE_N was observed in the UDP treatment for BRRI dhan67, while UDP and INM-2

Table 4

Grain yield, straw yield, total nitrogen uptake (TNU), agronomic efficiency of N (AE_N), recovery efficiency of N (RE_N), and physiological efficiency of N (PE_N) of Boro rice as influenced by fertilizer management, rice variety and year, and their interaction at Kaliganj, Satkhira.

Fertilizer treatment	Year	Grain yield (t ha ⁻¹)		Straw yield (t ha ⁻¹)		TNU (kg ha ⁻¹)		AE _N (kg grain kg ⁻¹ N)		RE _N (%)		PE _N (kg grain kg ⁻¹ N uptake)
		V1	V2	V1	V2	V1	V2	V1	V2	V1	V2	Mean of 2 cultivars
Effects of fertilizer treatment (means across year and variety)												
FP	Mean	4.6bA	2.7cB	4.6b	3.0b	68.6b	43.7b	18.5d	7.2d	29.9c	15.1d	55.2
UDP		5.0abA	3.1abcB	5.1ab	3.3ab	73.1b	46.9ab	37.8a	17.9a	58.7a	30.9a	61.0
OCP fertilizer		4.9abA	3.0abcB	4.8ab	3.2ab	74.2b	47.1ab	23.7c	10.8cd	39.0b	20.3cd	56.2
RFD		4.8abA	2.9bcB	4.9ab	3.1ab	71.3b	47.3ab	22.8c	9.6cd	36.6b	20.4cd	54.7
INM-1 (100 % RFD + ash)		4.6bA	3.2abB	4.7b	3.4ab	72.7b	51.6a	21.3cd	12.4bc	37.8b	23.9bc	52.9
INM-2 (70 % RFD with ash + cow dung)		5.2aA	3.4aB	5.3a	3.5a	86.1a	53.0a	30.4b	16.1ab	55.4a	28.5ab	54.7
N control		2.0cA	1.7dB	2.1c	1.8c	27.4c	22.8c	–	–	–	–	–
Effects of the year (means across variety and fertilizer treatment)												
Mean		Mean of 2 cultivars		Mean of 2 cultivars		Mean of 2 cultivars		V1	V2	Mean of 2 varieties		Mean of 2 cultivars
	2020	4.4a		4.4a		67.1a		31.0a	16.3a	39.0a		59.7
	2021	3.1b		3.1b		45.1b		20.5b	8.3b	27.0b		51.8
Effects of variety (means across year and fertilizer treatment)												
Mean	Mean	4.5A	3.1B	4.5A	3.1B	67.6A	44.6B	25.7A	12.3B	42.9A	23.2B	59.7A 51.9B
ANOVA (p values)												
Fertilizer (F)		*		*		*		*		*		ns
Variety (V)		*		*		*		*		*		*
Year (Y)		*		*		*		*		*		ns
F × V		*		*		*		*		*		ns
F × Y		*		*		*		*		*		ns
V × Y		ns		ns		ns		*		ns		ns
F × V × Y		ns		ns		ns		ns		ns		ns

For each response variable, means followed by the identical uppercase letters in a row and lowercase letters in a column do not differ significantly at a 5 % level of probability. FP, UDP, RFD, INM, V1, and V2 correspond to farmers' practice, urea deep placement, recommended fertilizer dose, integrated nutrient management, BRRI dhan67, and BRRI dhan88, respectively. * and ns denote significant, and non-significant at a 5 % level of probability, respectively.

treatments showed similar AE_N for BRRI dhan88. Both UDP and INM-2 treatments showed the highest RE_N compared to other treatments. There was no significant variation in PE_N among the treatments. However, across the fertilizer treatments, BRRI dhan67 demonstrated a significant ($p < 0.05$) increase in total nitrogen uptake, AE_N , and RE_N by 18 %, 23 %, and 26 %, respectively, at the BRRI farm, and 52 %, 109 %, and 85 % in Kaliganj compared to BRRI dhan88 (Tables 3 and 4).

3.5. CH_4 and N_2O emissions

CH_4 emission rates varied with fertilizer treatments and rice cultivars (Fig. 2). Two emission peaks were found in the maximum tillering and flowering stages throughout the rice-growing seasons irrespective of the cultivars (Fig. 2). The magnitudes of emissions peaks were greater in both integrated nutrient management (INM) treatments compared to the other treatments. However, the lowest CH_4 emission rates were observed in the urea deep placement (UDP) treatment across both cultivars (Fig. 2). CH_4 emission rates dropped during the drying period in both cultivars.

The interaction effects of fertilizer and cultivars on cumulative CH_4 emissions and emission factors were found to be insignificant (Table 5). Across the year and cultivars, UDP treatment gave lower cumulative CH_4 emissions by 17–31 % and emission factor 17–31 % compared to other treatments. The highest CH_4 emissions and emission factor were observed in both INM treatments. There was no significant variation in CH_4 emissions between the farmers' practice (FP) and recommended fertilizer dose (RFD) treatments. While comparing rice varieties, BRRI dhan67 demonstrated a significant ($p < 0.05$) reduction in CH_4 emissions and emission factor by 4.9 % and 5.1 %, respectively, compared to BRRI dhan88 (Table 5).

Emission rates of N_2O varied with fertilizer rates and sources during two consecutive Boro seasons of 2020 and 2021 under both varieties (Fig. 2). Prominent emission peaks of N_2O were observed after each top-dressing of N fertilizer application, except UDP. The magnitudes of emission peaks were more prominent in the first top-dressing period compared to other top-dressing. However, some emissions were found during a dry period for the harvest of rice plants (Fig. 2).

Fertilizer treatments and rice cultivars had insignificant interaction effects on cumulative N_2O emissions and emission factor of N_2O (Table 5). Across the year, UDP significantly ($p < 0.05$) reduced cumulative N_2O emission and emission factor by 54–67 % compared to other treatments. Although both INM treatments showed similar N_2O emissions, INM-2 gave 12 % lower emissions than INM-1 (Table 5). There were no significant variations in cumulative emission and emission factor of N_2O between the two rice varieties (Table 5).

3.6. Global warming potential and yield-scaled emissions of CH_4

Fertilizer management had an insignificant variation with rice cultivars on global warming potential (GWP) and yield-scaled emissions of CH_4 (Table 5). The higher GWP and yield-scaled emissions of CH_4 were found in both integrated nutrient management (INM) treatments compared to other treatments. Conversely, lower GWP (18–31 %) and yield-scaled emissions (23–28 %) were observed in the urea deep placement (UDP) treatment compared to other treatments. There were no significant variations in GWP and yield-scaled emissions between farmers' practice (FP) and recommended fertilizer dose (RFD) treatments. Across the fertilizer management and year, BRRI dhan67 gave lower GWP by 5 % and yield-scaled emissions of CH_4 by 22 % compared to BRRI dhan88.

3.7. Economic analysis

The higher fertilizer cost was associated with integrated nutrient management-1 (INM-1) treatment, while the lowest cost was involved in N control treatment in both locations of the BRRI farm and Kaliganj in

Satkhira (Table 6). At the BRRI farm, the highest return to fertilizer investment (RFI) and marginal benefit-cost ratio was recorded in INM-2, followed by UDP treatment for both BRRI dhan67 and BRRI dhan88. In contrast, the control treatment exhibited the lowest return to fertilizer investment and marginal benefit-cost ratio. Similarly, in Kaliganj, INM-1 treatment yielded the highest RFI, which closely approached the return to fertilizer investment of the UDP treatment for both cultivars. However, the magnitude of gross return, gross margin, return to fertilizer investment, and marginal benefit-cost ratio was higher at the BRRI farm compared to Kaliganj in Satkhira (Table 6).

Regarding cost-dominant analysis, the fertilizer costs for both cultivars were found to be similar in both locations (Table S3). Through the cost-dominant analysis, BRRI dhan88 was excluded from consideration in both locations, while BRRI dhan67 remained viable. Similarly, apart from the control, UDP, and INM-2 treatments, all other fertilizer treatments were eliminated. However, INM-2 exhibited a higher marginal rate of return compared to the UDP treatment in both locations, as shown in Table 7. Therefore, INM-2 treatment have the potential for higher profitability in both locations.

3.8. Risk analysis

At the BRRI farm in Satkhira, the probability of achieving a gross margin below the threshold of 50,000 Tk ha⁻¹ was lower for BRRI dhan67 (3.8 %). Conversely, the probability of a gross margin below the threshold of 50,000 Tk ha⁻¹ was higher for BRRI dhan88 (10.2 %) (Fig. 3). Similarly, BRRI dhan67 demonstrated a higher probability of achieving a gross margin above the threshold of 100,000 Tk ha⁻¹ compared to BRRI dhan88. This indicates that BRRI dhan67 has a greater chance of attaining a gross margin above the specified threshold, suggesting potentially better economic performance in terms of profitability compared to BRRI dhan88 at the BRRI farm in Satkhira. In terms of fertilizer management, integrated nutrient management-2 (INM-2) (92.1 %) exhibited a higher probability of achieving a gross margin above the threshold of 100,000 Tk ha⁻¹, followed by the urea deep placement (UDP) (91.0 %) treatment for BRRI dhan67. Similarly, comparable results for gross margin were observed for BRRI dhan88 (Fig. 3).

In Kaliganj, the probability of achieving a gross margin above the threshold of 100,000 Tk ha⁻¹ was higher for BRRI dhan67 (37.5 %), while it was lower for BRRI dhan88 (4.6 %) (Fig. 4). However, a higher probability of gross margin above the threshold of 100,000 Tk ha⁻¹ was recorded for INM-2 (74.7 %), followed by the UDP treatment (74.5 %) in BRRI dhan67. Similarly, the probability of gross margin above the threshold of 100,000 Tk ha⁻¹ was higher for INM-2 (6.5 %) in BRRI dhan88 (Fig. 4).

4. Discussion

4.1. Soil Salinity

Soil salinity adversely affects the growth and yield contributing characteristics of rice, and the severity of plant damage and yield reduction depends on the degrees of salinity, rice varieties, and the growth stages of plants (Shereen et al., 2005). In the coastal region of Bangladesh, soil salinity generally starts to rise in January and reaches a peak in April or May when the temperature rises with less rainfall (Bhuyan et al., 2023). In our present study, we also found that soil salinity increased with the progress of the season and reached a maximum during the reproductive phase of the rice plant. The reproductive phase of rice plants is highly sensitive to salt stress (Singh et al., 2021). However, soil salinity can be mitigated by different organic (Barzegar et al., 1997) and inorganic amendments (Islam et al., 2017). The present study found that integrated nutrient management-2 (INM-2) was highly efficient among the treatments to alleviate soil salinity and increase rice yield. The addition of organic matter may increase the total porosity, resulting in increased leaching of exchangeable Na⁺ and the

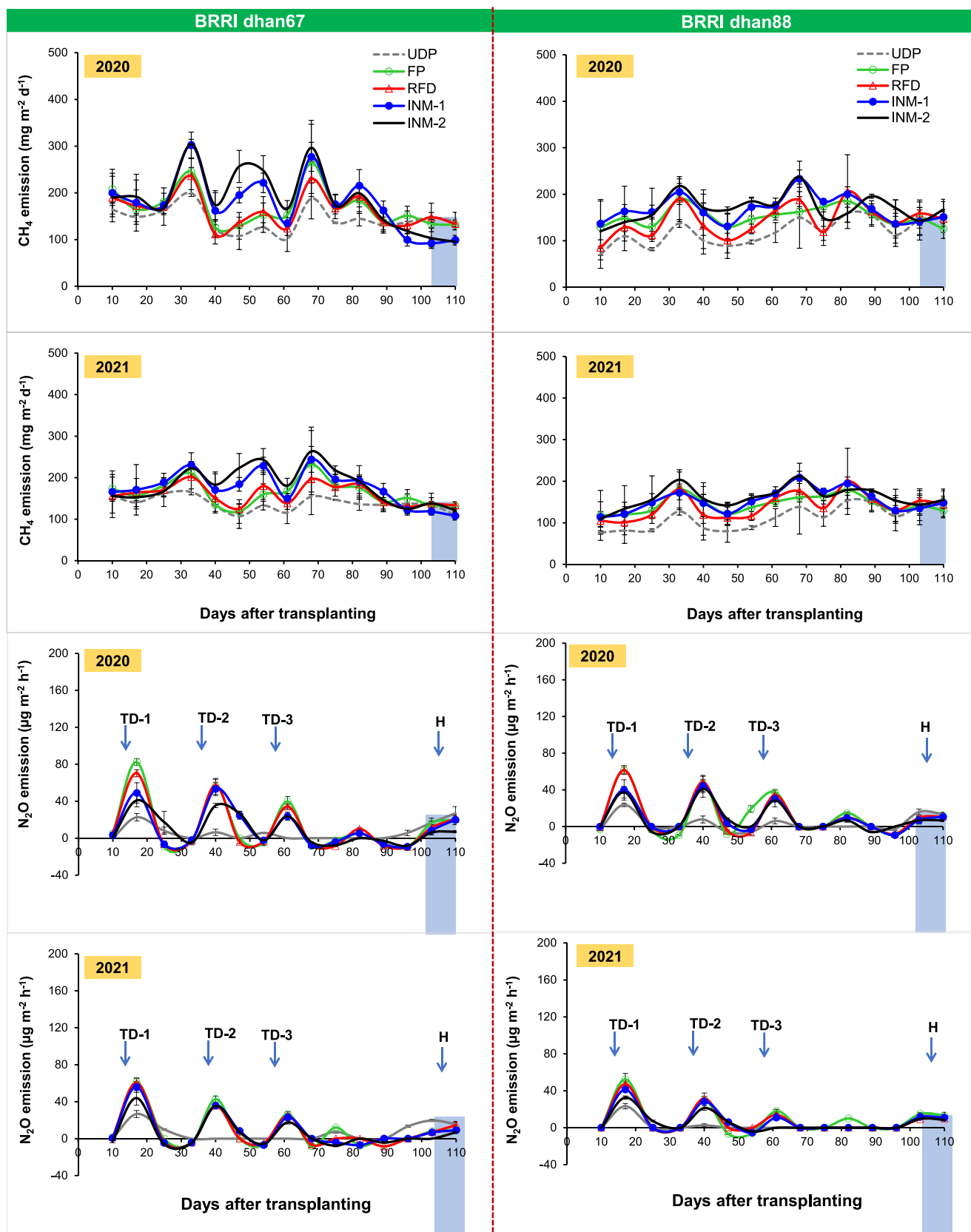


Fig. 2. Dynamics of CH₄ and N₂O emissions from different fertilizer treatments during Boro (dry) seasons at BRRI farm, Satkhira. FP, UDP, RFD and INM correspond to farmers' practice, urea deep placement, recommended fertilizer dose and integrated nutrient management, respectively. The error bar indicates the error of the mean ($n = 3$).

Table 5

The effects of variety, fertilizer management, and year on seasonal CH₄ and N₂O emissions, emission factor of CH₄ and N₂O, GWP, and YSE of CH₄ in the Boro season at BRRI farm, Satkhira.

Fertilizer treatment	Year	CH ₄ emission (kg ha ⁻¹)	EF of CH ₄ (kg ha ⁻¹ d ⁻¹)	YSE of CH ₄	N ₂ O emission (g ha ⁻¹)	EF of N ₂ O (g ha ⁻¹ d ⁻¹)	GWP						
		Mean of 2 varieties	Mean of 2 varieties	Mean of 2 varieties	Mean of 2 varieties	Mean of 2 varieties	Mean of 2 varieties						
Effects of fertilizer treatment (means across year and variety)													
FP	Mean	144.9b	1.33b	30.5ab	239.3a	2.20a	3977.8b						
UDP		115.8c	1.06c	22.1c	79.5d	0.73d	3148.1c						
RFD		139.6b	1.28b	28.5b	214.9ab	1.97ab	3828.9b						
INM-1 (100 % RFD + ash)		160.6a	1.47a	30.8a	196.4bc	1.80bc	4389.0a						
INM-2 (70 % RFD with ash + cow dung)		166.6a	1.53a	30.4ab	172.7c	1.58c	4546.4a						
Effects of the year (means across variety and fertilizer treatment)													
Mean	2020	149.1a	1.37a	31.0a	207.4a	1.90a	4082.2a						
	2021	141.9b	1.30b	25.9b	153.8b	1.41b	3874.0b						
Effects of variety (means across year and fertilizer treatment)													
Mean	Mean	V1 141.9B	V2 149.2A	V1 1.30B	V2 1.37A	V1 25.0B	V2 31.9A	V1 177.6A	V2 183.6A	V1 1.63A	V2 1.68A	V1 3878.9B	V2 4077.3A
ANOVA (p values)													
Fertilizer (F)		*		*		*		*		*		*	
Variety (V)		*		*		*		ns		ns		*	
Year (Y)		ns		ns		ns		*		*		ns	
F × V		ns		ns		ns		ns		ns		ns	
F × Y		ns		ns		ns		*		*		ns	
V × Y		ns		ns		*		ns		ns		ns	
F × V × Y		ns		ns		ns		ns		ns		ns	

Within a column, means followed by the same lowercase letters, and within a row for each response variable, means followed by the same uppercase letters are not significantly different at a 5% level of probability by Tukey's honest significant difference (HSD) test. FP, UDP, RFD, INM, V1 and V2 correspond to farmers' practice, urea deep placement, recommended fertilizer dose, integrated nutrient management, BRRI dhan67 and BRRI dhan88, respectively.

Table 6

Fertilizer cost, gross return, gross margin, returns to fertilizer investment, and marginal benefit-cost ratio at the coastal saline zone of BRRI farm and Kaliganj in Satkhira.

Fertilizer management	Fertilizer cost (Tk ha ⁻¹)		Gross return (Tk ha ⁻¹)		Gross margin (Tk ha ⁻¹)		Returns to fertilizer investment (Tk ha ⁻¹)		MBCR (over N control)	
	BRRI dhan67	BRRI dhan88	BRRI dhan67	BRRI dhan88	BRRI dhan67	BRRI dhan88	BRRI dhan67	BRRI dhan88	BRRI dhan67	BRRI dhan88
BRRI farm, Satkhira										
FP	18,574	18,574	175,200	145,200	156,626	126,626	9.43	7.82	12.20	9.44
UDP	17,557	17,557	195,600	158,400	178,043	140,843	11.14	9.02	16.65	12.54
OCP fertilizer	17,582	17,582	182,100	148,500	164,518	130,918	10.36	8.45	14.77	11.16
RFD	18,018	18,018	178,200	151,800	160,182	133,782	9.89	8.43	13.45	10.96
INM-1 (100 % RFD + ash)	21,018	21,018	191,400	161,400	170,382	140,382	9.11	7.68	10.94	8.81
INM-2 (70 % RFD with ash + cow dung)	18,000	18,000	204,300	171,000	186,300	153,000	11.35	9.50	16.82	13.44
N control	10,187	10,187	72,900	66,000	62,713	55,813	7.16	6.48	–	–
Average	17,277	17,277	171,386	143,186	154,109	125,909	9.78	8.20	14.14	11.06
Kaliganj, Satkhira										
FP	18,574	18,574	151,800	90,000	133,226	71,426	8.17	4.85	10.19	4.01
UDP	17,557	17,557	165,300	102,900	147,743	85,343	9.42	5.86	13.43	6.31
OCP fertilizer	17,582	17,582	161,400	99,600	143,818	82,018	9.18	5.66	12.86	5.84
RFD	18,018	18,018	158,700	96,300	140,682	78,282	8.81	5.34	11.80	5.10
INM-1 (100 % RFD + ash)	21,018	21,018	152,100	106,200	131,082	85,182	7.24	5.05	7.92	4.60
INM-2 (70 % RFD with ash + cow dung)	18,000	18,000	171,900	112,500	153,900	94,500	9.55	6.25	13.52	7.18
N control	10,187	10,187	66,300	56,400	56,113	46,213	6.51	5.54	–	–
Average	17,277	17,277	146,786	94,843	129,509	77,566	8.41	5.51	11.62	5.51

FP, UDP, RFD, INM, Tk, and MBCR correspond to farmers' practice, urea deep placement, recommended fertilizer dose, integrated nutrient management, Bangladeshi currency in Taka, and marginal benefit-cost ratio, respectively. 1 US dollar to Bangladesh Taka exchange rate was 110.5 (Source: Bangladesh Bank; 30 October 2023).

subsequent reduction in soil EC (Barzegar et al., 1997; Tejada et al., 2008), which might be the plausible reason for increased rice yield.

4.2. Yield and yield contributing characters

Our results showed that the combined application of organic and inorganic fertilizers as integrated nutrient management (INM) and urea deep placement (UDP) significantly increased rice yield and yield

Table 7
Marginal analysis of undominated treatments at the coastal saline zone of BRRI farm, and Kaliganj in Satkhira.

Fertilizer cost (Tk ha ⁻¹)	Fertilizer management	Rice varieties	Gross margin (Tk ha ⁻¹)	Marginal fertilizer cost (Tk ha ⁻¹)	Marginal gross margin (Tk ha ⁻¹)	Marginal rate of return (%)
BRRI farm, Satkhira						
10,187	N control	BRRI dhan67	62,713	–	–	–
17,557	UDP	BRRI dhan67	178,043	7370	115,330	1565
18,000	INM-2 (70 % RFD with ash + cow dung)	BRRI dhan67	186,300	443	8257	1864
Kaliganj, Satkhira						
10,187	N control	BRRI dhan67	56,113	–	–	–
17,557	UDP	BRRI dhan67	147,743	7370	91,630	1243
18,000	INM-2 (70 % RFD with ash + cow dung)	BRRI dhan67	153,900	443	6157	1390

1 US dollar to Bangladesh Taka exchange rate was 110.5 (Source: Bangladesh Bank). UDP, RFD, and INM correspond to urea deep placement, recommended fertilizer dose, and integrated nutrient management, respectively.

contributing characters in both rice varieties (BRRI dhan67 and BRRI dhan88) (Tables 3 and 4). The INM treatments decreased soil salinity (Fig. 1), which might increase tiller and panicle number, filled grain, and grain per panicle (Tables S1 and S2), resulting in increased grain yield. The application of organic manure, in addition to inorganic fertilizer, could improve the water-holding capacity, soil aggregates, and chemical and biological properties of saline soil (Yaduvanshi and Swarup, 2005; Mao et al., 2022). It also promotes good microbial activity, which helps rice roots absorb and mobilize nutrients. Consequently, the rice plants develop more effectively, are less stressed by salt, and are more resilient to saline environments. Moreover, the application of cow dung and ash might be played a significant role in increasing soil porosity, which enhances the leaching of Na⁺ from the exchange site of the soil profile (Barzegar et al., 1997; Leogrande and Vittì, 2019; Lee et al., 2022). Furthermore, the use of cow dung and ash may increase cation exchange capacity and ion adsorption with clay particles, lowering the soluble salt concentration in the soil solution. (Leogrande and Vittì, 2019). In addition, organic amendment and inorganic fertilizers under INM treatments might be considered an important source of Ca²⁺ and K⁺, which may replace the exchangeable Na⁺ from the exchange sites, thus it might reduce soil salinity and enhancing crop growth (Leogrande and Vittì, 2019; Chen et al., 2021).

Urea deep placement yielded similar results to the INM-2 treatments for both BRRI dhan67 and BRRI dhan88 in the studied locations (Tables 3 and 4). The increase in grain yield under UDP treatment might be associated with a higher number of effective tillers, filled grain, and grain per panicle production (Tables S1 and S2). This could be attributed to the deep placement of N fertilizer in the reduced zone, which enables the prolonged presence of non-exchangeable NH₄⁺ in the root zone due to contact with the N fertilizer and soil particles and ensures a continuous supply of N throughout the rice-growing season (Liu et al., 2015). In addition, the ionic radius of NH₄⁺ (0.175 nm) is relatively higher compared to Na⁺ (0.102 nm), and their charges are also similar; hence, NH₄⁺ could replace the Na⁺ from the root zone, resulting in lowering salinity, which could enhance root growth and crop development (Sugiura et al., 2021; Angin et al., 2022). The 1000-grain weight remained consistently stable across all treatments in this study, which is in line with previous findings (Fageria et al., 2011).

Across the fertilizer treatments, BRRI dhan67 produced a significant ($p < 0.05$) increase in rice yield by 18 % and 45 % compared to BRRI dhan88 at the BRRI farm and Kaliganj in Satkhira, respectively (Tables 3 and 4). The higher yield observed in BRRI dhan67 can be attributed to its salt-tolerant nature, which contributes to the production of more effective tillers, filled grain, and grain per panicle, while also reducing the occurrence of unfilled grain. These characteristics are influenced by

the genetic makeup of this particular cultivar, as supported by the data presented in Tables S1 and S2. Our findings support the previous research (Ali et al., 2014; Djaman et al., 2019). The salt-tolerant rice cultivars probably translocate less Na⁺ from the shoot to the roots, allowing more K⁺ and Ca²⁺ to the shoot instead of Na⁺ resulting in less Na⁺/K⁺ ratio in plant tissue (Alam et al., 2002). Moreover, they could belong to a large root surface area for absorbing nutrition from stress conditions and contain high protein and proline contents that act as a cytoplasmic osmoticum to sustain the osmotic balance (Ali et al., 2014; Djaman et al., 2019). BRRI dhan67 exhibited a yield variation of only 70 % between the two locations, whereas BRRI dhan88 showed a yield variation of 130 % (Tables 3 and 4). This disparity can be attributed to variations in soil salinity levels (Fig. 1). As BRRI dhan67 is a salt-tolerant cultivar, it showed less yield variation relative to the BRRI dhan88, a salt-sensitive cultivar.

4.3. Nitrogen uptake and nitrogen use efficiency

In general, the higher N rate showed higher total nitrogen uptake. Although farmers' practice (FP) and recommended fertilizer dose (RFD) fertilizers contain higher N rates, they produced lower total nitrogen uptake compared to the application of organic and inorganic fertilizers as integrated nutrient management (INM) treatments in both locations (Tables 3 and 4). Lower total nitrogen uptake is probably associated with the presence of a higher concentration of soluble salts (Na⁺, Ca²⁺, Mg²⁺) in saline soil, leading to ion toxicity, which inhibits the metabolic processes such as protein synthesis and photosynthetic activities of the cell, resulting in reducing biomass accumulation and translocation, and water and nutrients uptake (Ismail and Horie, 2017). On the other hand, higher total nitrogen uptake under INM treatments could be due to reduced soil salinity (Fig. 1), higher total aboveground biomass (Tables 3 and 4), and ensures a steady supply of nutrients throughout the rice growing seasons. It improves the activity of beneficial microorganisms that can help in the mineralization of organic nitrogen into forms that are easily available to plants, leading to higher total nitrogen uptake and nitrogen use efficiency (Wichern et al., 2020). Moreover, the combined application of organic and inorganic fertilizers could improve water holding capacity, soil enzymatic activities (urease, phosphatase, dehydrogenase), and soil microbial biomass, which could help to alleviate the negative impacts of salinity by counteracting osmotic stress, resulting in minimizing nutritional imbalance and enhance nutrient uptake (Liang et al., 2003; Wichern et al., 2020). Although INM treatment gave higher rice yield, it produced lower agronomic efficiency of N (AE_N) due to higher N rates than urea deep placement (UDP). However, UDP and INM-2 treatments showed similar recovery efficiency of N

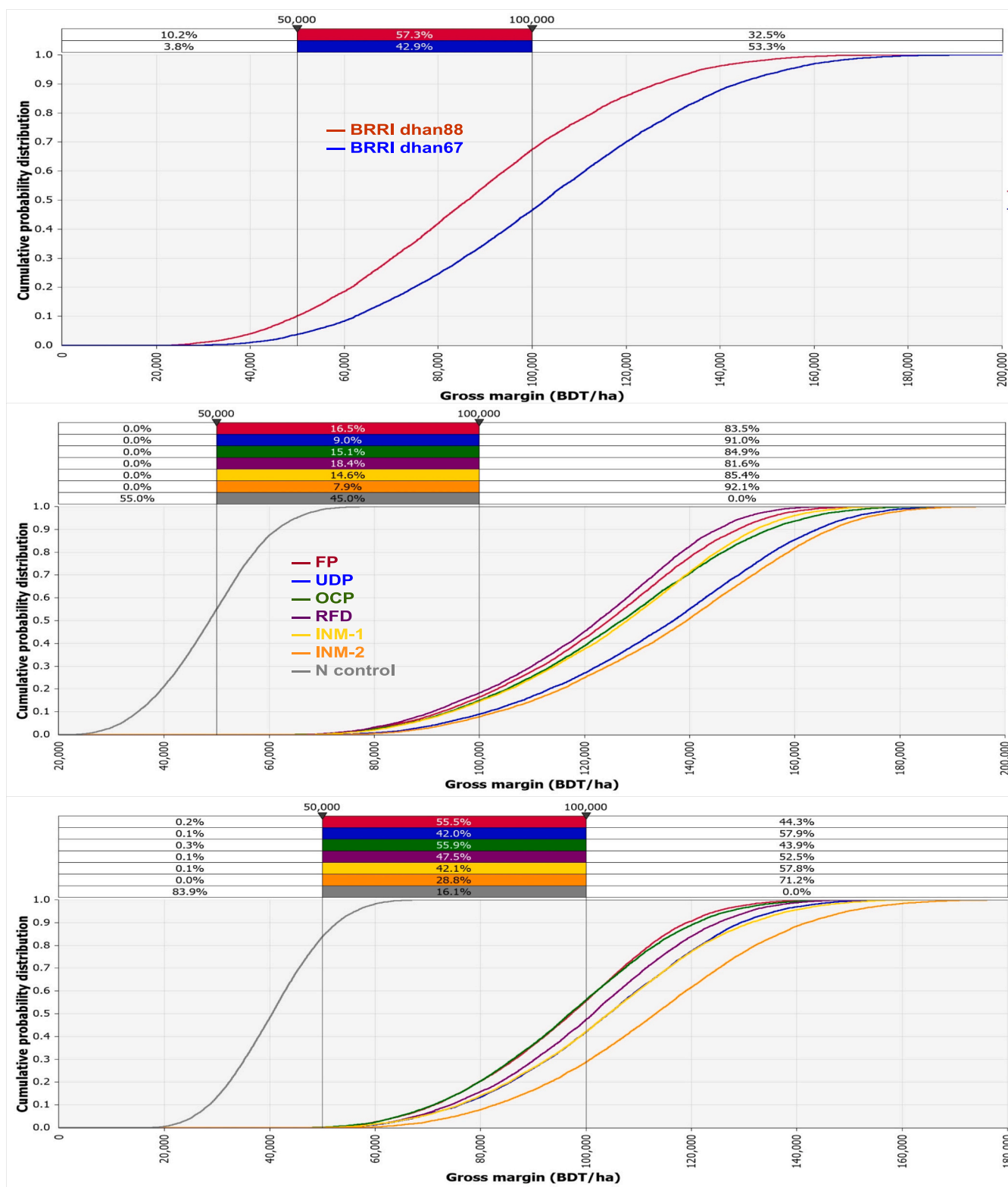


Fig. 3. Cumulative probability distribution of gross margin of BRRi dhan67 and BRRi dhan88 at fertilizer management variation in yield at BRRi farm in Satkhira. The middle and bottom of the figures represent BRRi dhan67 and BRRi dhan88, respectively. Here, BDT denotes Bangladeshi currency in Taka.

(RE_N), which could be associated with higher grain yield and total nitrogen uptake (Tables 3 and 4). Our results align with previous findings (Liu et al., 2015; Islam et al., 2016, 2018). The reason for higher AE_N and RE_N could be due to non-exchangeable NH₄⁺ in the rhizosphere and larger root volume, which could secrete proton led to reduced pH in the root zone that favors crop growth under saline soil (Bustamante et al.,

2016), thus improving rice yield and nitrogen use efficiency. Similarly, INM treatment reduced soil salinity (Fig. 1) and could improve soil quality by providing additional C and N to the soil (Chen et al., 2021), enhancing nutrient uptake and nitrogen use efficiency. In contrast, there was no significant variation in the physiological efficiency of N (PE_N) between UDP and INM-2 treatments due to higher grain yield and total

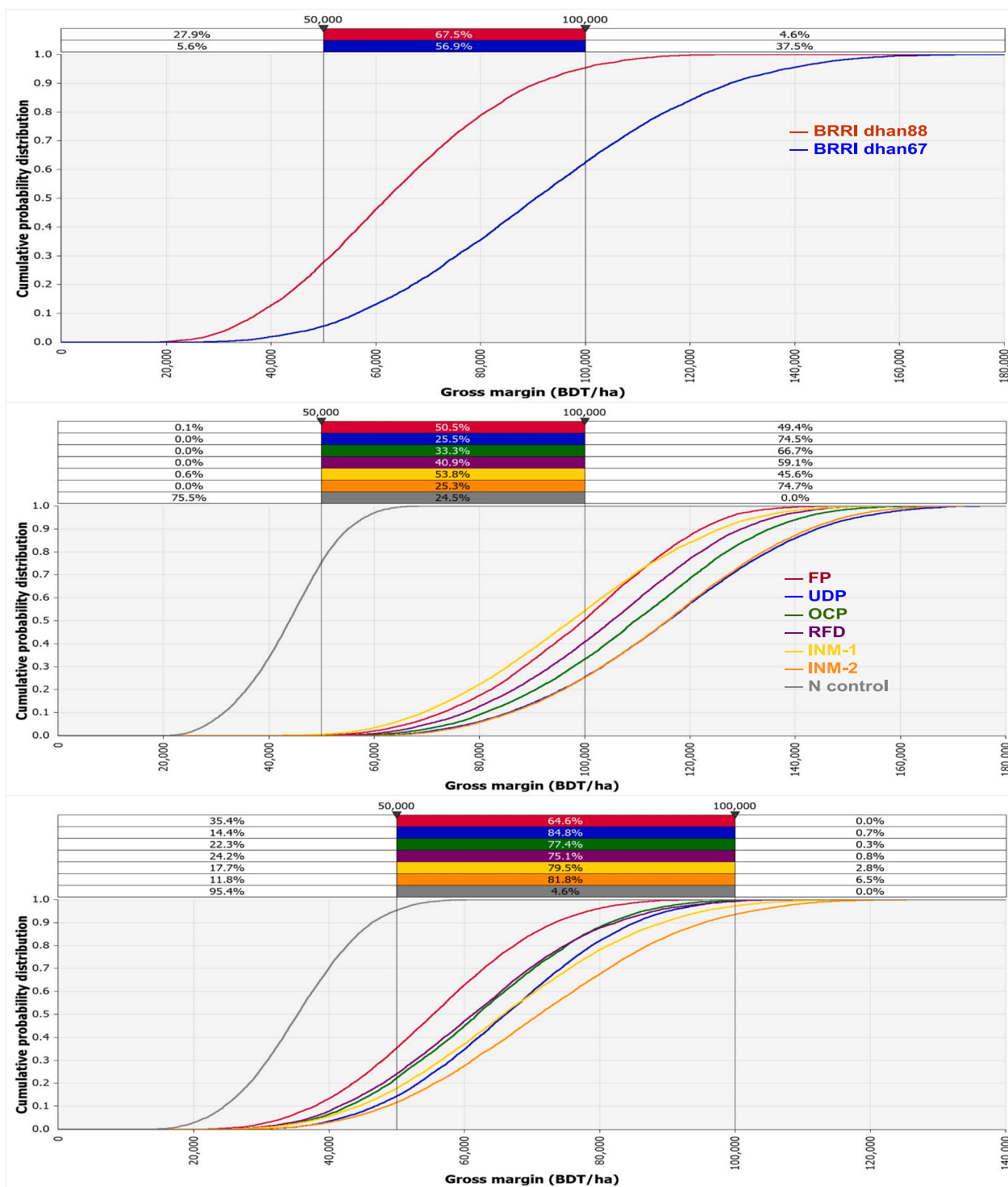


Fig. 4. Cumulative probability distribution of gross margin of BRRi dhan67 and BRRi dhan88 at fertilizer management variation in yield in Kaliganj, Satkhira. The middle and bottom of the figures represent BRRi dhan67 and BRRi dhan88, respectively. Here, BDT denotes Bangladeshi currency in Taka.

nitrogen uptake (Tables 3 and 4). However, our findings show that BRRi dhan67 significantly increased nitrogen use efficiency across the fertilizer treatments in both locations compared to BRRi dhan88.

4.4. CH₄ and N₂O emissions

Reducing greenhouse gas emissions and maintaining food security are major concerns in Bangladesh. Incorporating different fertilizer sources and rice cultivars is seen as a potential solution to address these

challenges. Greater CH₄ emissions in both integrated nutrient management (INM) treatments (Table 5) could be linked to dissolved organic carbon derived from the decomposition of organic substances leading to additional C substrate for the methanogenic bacteria (Kimani et al., 2020; Islam et al., 2022a, 2022b). Our results are in line with the previous findings (Islam et al., 2020, 2022c, 2022d). In addition, INM treatments could provide labile organic C, which increases microbial and enzymatic activities, and reduces redox potential, thus resulting in higher CH₄ emissions (Kimani et al., 2020). In contrast, the UDP

treatment significantly ($p < 0.05$) reduced CH_4 emissions by 17–31 % compared to other treatments (Table 5). Lower CH_4 emissions under UDP treatments might be associated with CH_4 oxidation by the soil methanotrophs due to the retention of available $\text{NH}_4^+\text{-N}$ for a longer period in the subsurface soil (Bodelier et al., 2000). In addition, the UDP in the reduced zone (8–10 cm below the soil surface) could increase total root volume, which increased O_2 availability in the rhizosphere would like to enhance CH_4 consumption in the subsurface soils and subsequent reduction of CH_4 emissions (Gilbert and Frenzel, 1998). UDP also enhanced soil microbial and bacterial biomass increased the labile soil organic carbon fractions, and decreased the methanogens/methanotrophs ratio—all of which contributed to a decrease in CH_4 emissions (Fan et al., 2020). Our findings are consistent with the results of the previous literature (Liu et al., 2020; Islam et al., 2022c, 2022d).

Rice cultivars have an important role in regulating CH_4 emissions in rice fields, and significant variations in CH_4 emissions of different rice cultivars have been observed in earlier studies (Ding et al., 2022; Habib et al., 2023). In our study, BRRI dhan67 significantly ($p < 0.05$) reduced CH_4 emissions by about 5 % compared to BRRI dhan88 (Table 5). Since BRRI dhan67 is a salt-tolerant rice cultivar, it produced more yield compared to BRRI dhan88 in saline soil (Tables 3 and 4). High-yielding rice cultivars could possess low methane transport capacity (MTC), which could play a significant role in low CH_4 emissions in BRRI dhan67 (Luke et al., 2011). Due to coping up salinity, BRRI dhan67 grew more and stronger root systems that could transport more O_2 in the rhizosphere soil, and increase soil aeration, thus improving soil redox potential and creating a suitable environment for the methanotrophs which enhances CH_4 oxidation (Chen et al., 2019; Ding et al., 2022). Moreover, due to higher grain yield in BRRI dhan67, it could allocate more photosynthate for grain filling, resulting in lower CH_4 emissions (Baruah et al., 2010; Chen et al., 2021).

In the present study, UDP had a significant effect in reducing N_2O emissions and emission factor compared to other treatments under both varieties (Table 5), which is in line with previous studies (Gaihre et al., 2015, 2018; Islam et al., 2022d). The slow movement of $\text{NH}_4^+\text{-N}$ from the reduced zone, which results in a minimum presence of $\text{NH}_4^+\text{-N}$ in the surface soil layer or floodwater, may be responsible for the lowered emissions of N_2O when applying UDP treatment (Kapoor et al., 2008; Rochette et al., 2013). On the other hand, higher N_2O emissions and emission factor under FP and recommended fertilizer dose (RFD) treatments resulting from broadcast prilled urea may be explained by the nitrification of $\text{NH}_4^+\text{-N}$ to NO_3^- and subsequent denitrification of NO_3^- (Sander et al., 2014; Gaihre et al., 2015). The combined effects of inorganic (prilled urea) and organic (cow dung or ash) amendments, which make carbon and nitrogen readily available to the soil, are likely the cause of IPNS treatments' increased emissions compared to UDP (Shakoor et al., 2021; Islam et al., 2022d). However, similar variations in N_2O emissions and emission factor between the two rice cultivars in this study are consistent with previous study (Simmonds et al., 2015).

4.5. Global warming potential and yield-scaled emissions

Across the cultivars, higher global warming potential (GWP) was observed in both integrated nutrient management (INM) treatments compared to other treatments due to higher cumulative CH_4 and N_2O emissions (Table 5), which is consistent with previous findings (Kimani et al., 2020; Islam et al., 2022c, 2022d). In contrast, compared to other treatments, urea deep placement (UDP) treatment significantly decreased GWP and yield-scaled emissions by about 18–31 % and 23–28 %, respectively (Table 5). Lower GWP and yield-scaled emissions under UDP treatment are probably linked to reduced cumulative CH_4 and N_2O emissions (Table 5) and higher rice yields (Tables 3 and 4), which aligns with earlier reports (Islam et al., 2022c, 2022d). Despite having a higher radiative forcing of N_2O than CH_4 , N_2O contributed 1.2 % of the total GWP in this study, which is consistent with previous studies (Sander et al., 2014; Islam et al., 2020).

BRRI dhan67 reduced the GWP and yield-scaled emissions of CH_4 by about 4.9 % and 21.6 %, respectively, compared to BRRI dhan88. Lower GWP under BRRI dhan67 could be described by a higher rice yield because of allocating more photosynthate to grain formation and below-ground biomass, thereby reducing CH_4 emissions and subsequent GWP and yield-scaled emissions (Baruah et al., 2010; Chen et al., 2021). Therefore, BRRI dhan67 could be a great option to increase rice yield in saline soil while ensuring food security and minimizing the negative impacts of climate change.

4.6. Economic viability

Our findings suggest that BRRI dhan67, especially when combined with integrated nutrient management-2 (INM-2) or urea deep placement (UDP) treatments, has a higher potential for achieving higher gross margin and better economic performance in terms of profitability compared to BRRI dhan88 in the saline coastal ecosystem of Bangladesh. Specifically, the higher return to fertilizer investment and marginal benefit-cost ratio under INM-2 treatment might be associated with low fertilizer cost and higher gross return from higher biomass yield. Although the UDP treatment gave lower fertilizer cost than the INM-2 treatment, it gave higher gross margin, resulting in higher marginal rate of return in the INM treatment in both locations (Table 6 and 7). Moreover, for getting gross margin above the threshold of 100,000 Tk ha^{-1} , INM-2 treatment might be economically viable due to showing less production and market risk irrespective of locations (Figs. 3 and 4). While fertilizer management had a significant impact on rice yield for both BRRI dhan67 and BRRI dhan88, cost-dominant analysis automatically excluded BRRI dhan88 and all fertilizer treatments, except for the INM-2 and UDP treatments, at both locations (Table S3). Therefore, the UDP and INM-2 treatments can be regarded as economically profitable technologies for BRRI dhan67 in the coastal saline zone of Bangladesh. The reasons for the economic viability of the INM-2 and UDP treatments can be attributed to their lower fertilizer costs and higher biomass yields. The mechanism behind the increase in biomass yield is elaborated upon in Sections 4.1 and 4.2. In the context of farming, the salt-tolerant variety outperforms the non-salt-tolerant varieties in terms of yield and profitability under saline soil conditions. This means that the salt-tolerant variety is less prone to yield losses and offers higher financial returns, making it a more favorable choice for farmers dealing with soil salinity issues. Our results are consistent with the previous findings (Ghosh et al., 2022; Sutardi et al., 2022).

5. Conclusions

Soil salinity, a major constraint to agricultural productivity, demands innovative solutions, and integrated nutrient management offers a promising pathway. The implementation of integrated nutrient management, combined application of organic and inorganic amendments, strategies represents a significant leap forward in addressing the challenges posed by saline soils in rice cultivation. This study suggests that a combination of inorganic and organic amendments, and the use of salt-tolerant rice cultivar proves to be an effective approach in reducing soil salinity while simultaneously increasing rice yield, nitrogen use efficiency and gross margin. The degree of increment of marginal rate of return was also greater in the INM-2 treatment. However, UDP might be a good approach in reducing global warming potential and increasing rice yield, although the degree of increment of marginal rate of return was lower in the UDP treatment compared to the INM-2 treatment.

Since our study considered only two rice cultivars and two locations, it may limit the generalizability of the findings to other rice cultivars, and different soil and environmental conditions in the coastal saline ecosystem. Future studies could benefit from using a wider range of rice cultivars to gain a deeper knowledge of how different cultivars react to different conditions. Extrapolating the study to different geographical areas with different soil types will make the results more applicable and

relevant.

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CRediT authorship contribution statement

Conception and design: S.M.M.I., Y.K.G., U.S. and A.A.M; Analysis and investigation: S.M.M.I., M.R.I., A.I., M.N.I., M.A. and A.J; Draft conceptualization: S.M.M.I., M.R.I., A.I., A.J. and M.A.R.S; Writing - original draft preparation: S.M.M.I. and Y.K.G; Writing - review and editing: S.M.M.I., Y.K.G., U.S., M.N.I., M.A.R.S., M.R.I., A.I. and M.A; Funding acquisition: Y.K.G. and A.A.M; All authors read and approved the final 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.

Data availability

Data will be made available on request.

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