Integrated nutrient management and urea deep placement improve rice yield, nitrogen use efficiency and farm profits without affecting methane emissions in saline soils of Bangladesh

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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 cultivar could play a crucial role to improve yield and promote low-carbon agriculture across saline soils. A two-year multi-location field experiment was conducted during the Boro (dry) season to investigate the effects of fertilizer management and rice cultivar selection on rice yield, economic viability, and environmental sustainability 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 (INM-N84) significantly ($p<0.05$) increased rice yield and nitrogen use efficiency (NUE) compared to other treatments for both BRRI dhan67 and BRRI dhan88. Similarly, INM-N84 gave a higher return on fertilizer investment and marginal benefit-cost ratio than other treatments in both locations and under both cultivars. BRRI dhan67 outperformed BRRI dhan88, significantly ($p<0.05$) increasing rice yield by 21% and 52% at the BRRI farm and Kaliganj in Satkhira, respectively. Cost-dominant analysis excluded BRRI dhan88 and all fertilizer treatments, except UDP and INM-N84, from consideration in both locations. Consequently, INM-N84 and UDP proved to be economically viable in both locations, with INM showing a higher marginal rate of return than UDP in BRRI dhan67. In terms of environmental sustainability, UDP significantly ($p<0.05$) reduced global warming potential (GWP) and yield-scaled emissions (YSE) of CH_4 by 31% and 38% without causing yield loss compared to INM-N84. Similarly, BRRI dhan67 significantly ($p<0.05$) reduced GWP and YSE of CH_4 by 5 and 22% compared to BRRI dhan88. These findings suggest that selecting optimal 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.

Keywords: BRRI dhan67; BRRI dhan88; farmers' practice; yield-scaled emissions; marginal rate of return; risk analysis

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 intrusion of seawater, which is directly affected by climate change (Cassia et al., 2018). Salinity level further increased with the increased temperature once evapotranspiration is higher than 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 Sjored et al., 2017). Soil salinity is a serious constraints to crop productivity in the coastal area of Bangladesh (Rahman et al., 2020). This area covers more than 30% of the country's cultivable land, and 63% of this coastal area is affected by various degrees of salinity and reducing 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 not supporting for sustainable crop production. However, there are different approaches and strategies are available to cope with agriculture production in saline soil. For example, use of salt-tolerant cultivar is one of the most effective approach 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, use of organic matter amendment is another important way to improve plant growth in saline soil, as they enhance salt leaching and improve 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 an increase of greenhouse gas (GHG) emissions. previous studies have reported that urea deep placement (UDP) and/or integrated nutrient management (INM) combining inorganic and organic manure could be effective to increase crop yield without increasing GHG emissions (Islam et al., 2020; Ding et al., 2022). In addition to fertilizer management, selection of appropriate rice cultivars could reduce GHG 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' practice on GHG 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 GHG emissions and soil salinity in the coastal saline region of Bangladesh. This study hypothesized that INM in combination with salt-tolerant rice cultivars would be a suitable technique for reducing soil salinity and GHG 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 (BRRI) 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 200 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.

<Table 1 here>

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 (hereafter called urea deep placement: UDP) at 78 kg N ha^{-1}; (iii) OCP fertilizer (9.4% N, 20% P, 5% S, and 1% Zn) at 110 kg N ha^{-1}; (iv) soil test based (STB) fertilizer at 120 kg N ha^{-1}; (v) integrated nutrient management (INM-N120), consisting 100% STB and ash at 2 t ha^{-1}; (vi) INM-N84, consisting of 70% STB 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, STB, and both INM treatments were considered for the CH_4 gas measurement. 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 of PU) 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 (62500 briquettes per ha). The size of the experimental plot was 5 m × 6 m.

<Table 2 here>

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 12-14 dS m^{-1} at the seedling stage and about eight dS m^{-1} 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 water, weed, and pest management were maintained as per BRRI's recommendations. 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. 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, OCP fertilizer was applied. Nutrient contents from organic fertilizer were adjusted with chemical fertilizer during the calculation of nitrogen use efficiency (NUE).

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 selected at random 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 hours. 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 (NUE) 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.

$$PE_N = \frac{G_f - G_C}{U_f - Uc}$$

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 CH_4 emissions

A detailed gas sampling method was described earlier by Islam et al. (2020). In brief, CH_4 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-min 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.

CH_4 gas concentration was measured using gas chromatography (Shimadzu GC-2014, Japan) equipped with a flame ionization detector (FID). The slope of the linear regression curves of gas concentration versus chamber closure time was used to calculate CH_4 emission rates (Islam et al., 2020).

The following equation was used to compute the GWP of CH_4:

$$\text{GWP (kg CO}_2\text{ equivalent ha}^{-1}\text{)} = (\text{TCH}_4 \times 28)$$

Where, TCH_4 is the total amount of CH_4 emission (kg ha^{-1}), 28 is the GWP value for CH_4 to CO_2 over a 100-year time horizon (IPCC, 2014).

The following equation was used to measure yield-scaled emission (YSE) of CH_4 (kg t^{-1} grain yield):

$$\text{YSE} = \frac{\text{Cumulative } CH_4 \text{emissions}}{\text{Yield}}$$

Emission factor (EF) of CH_4 (kg ha^{-1} d^{-1}) was determined using the following equation:

$$\mathrm{EF} = \frac{\text{Cumulative } CH_4\text{emissions}}{\text{Active growth periods}}$$

2.8. Economic analysis

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

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

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

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. To ensure the stability of the risk and return trade-off distribution, a total of 10,000 iterations were performed during the simulation (Lien, 2003).

2.10. Data analysis

Data on rice yield and yield contributing characters, NUE, CH_4 emissions, emission factors (EF), global warming potential (GWP), and yield-scaled emission (YSE) 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 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 BRRI farm in Satkhira (Fig. 1).

<Fig. 1 here>

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

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 and panicle production were observed in INM-N84 treatment (70% STB fertilizer with ash and cow dung) compared to farmers' practice (FP), OCP fertilizer, and STB treatments at BRRI farm, while in Kaliganj, they were higher in INM-N84 compared to all other treatments. Similarly, the greater filled grain was found in INM-N84 compared to FP and STB treatments, respectively under both locations. Except for the control treatment, there were no significant variations observed in the grain per panicle among the other treatments. Similarly, there was no significant variation observed in the 1000-grain weight across the treatments in both locations. However, BRRI dhan67 showed significant improvements ($p<0.05$) in tiller, panicle, filled-grain, grain per panicle, and 1000-grain weight compared to BRRI dhan88. Additionally, BRRI dhan67 gave a lower percentage of unfilled grains compared to 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 INM-N84 gave higher grain yield relative to FP, OCP fertilizer, and STB treatments under both BRRI dhan67 and BRRI dhan88. Similarly, INM-N84 produced a higher straw yield compared to FP and STB 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).

<Table 3 here>

In Kaliganj, a higher grain yield was observed in INM-N84 compared to FP and INM-N120 treatments under BRRI dhan67. Similarly, a higher grain yield was observed in INM-N84 compared to FP and STB treatments (Table 4). As in grain yield, higher straw yield was found in INM-N84 than 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).

<Table 4 here>

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 (TNU), agronomic efficiency of N (AE_N), and recovery efficiency of N (RE_N). However, it was found to be insignificant for the physiological efficiency of N (PE_N) under both locations (Tables 3 and 4). At the BRRI farm, both INM treatments gave higher TNU compared to other treatments for both BRRI dhan67 and BRRI dhan88 (Table 3). UDP and INM-N84 treatments showed similar RE_N and PE_N. However, UDP significantly ($p<0.05$) increased AE_N compared to other treatments for both cultivars. In Kaliganj, INM-N84 resulted in higher TNU compared to FP for both cultivars (Table 4). The highest AE_N was observed in the UDP treatment for BRRI dhan67, while UDP and INM-N84 treatments showed similar AE_N for BRRI dhan88. Both UDP and INM-N84 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 TNU, 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 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 INM treatments compared to the other treatments. However, the lowest CH_4 emission rates were observed in the 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 (EF) were found to be insignificant (Table 5). Across the year and cultivars, UDP treatment gave lower cumulative CH_4 emissions and EF compared to other treatments. The highest CH_4 emissions and EF were observed in both INM treatments. There was no significant variation in CH_4 emissions between the FP and STB treatments. While comparing rice varieties, BRRI dhan67 demonstrated a significant ($p<0.05$) reduction in CH_4 emissions and EF by 4.9% and 5.1%, respectively, compared to BRRI dhan88 (Table 5).

<Table 5 here>

3.6. GWP and YSE of CH_4

Fertilizer management had an insignificant variation with rice cultivars on GWP and yield-scaled emissions (YSE) of CH_4 (Table 5). The higher GWP and YSE of CH_4 were found in both INM treatments compared to other treatments. Conversely, lower GWP and YSE were observed in the UDP treatment compared to other treatments. There were no significant variations in GWP and YSE between FP and STB treatments. Across the fertilizer management and year, BRRI dhan67 gave lower GWP and YSE of CH_4 compared to BRRI dhan88.

3.7. Economic analysis

The higher fertilizer cost was associated with INM-N120 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 MBCR was recorded in INM-N84, followed by UDP treatment for both BRRI dhan67 and BRRI dhan88. In contrast, the control treatment exhibited the lowest RFI and MBCR. Similarly, in Kaliganj, INM-N84 treatment yielded the highest RFI, which closely approached the RFI of the UDP treatment for both cultivars. However, the magnitude of gross return, gross margin (GM), RFI, and MBCR was higher at the BRRI farm compared to Kaliganj in Satkhira (Table 6).

<Table 6 here>

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-N84 treatments, all other fertilizer treatments were eliminated. However, INM-N84 exhibited a higher MRR compared to the UDP treatment in both locations, as shown in Table 7. Therefore, both INM-N84 and UDP treatments have the potential for higher profitability in both locations.

<Table 7 here>

3.8. Risk analysis

At the BRRI farm in Satkhira, the probability of achieving a gross margin (GM) below the threshold of 50,000 Tk ha^{-1} was lower for BRRI dhan67 (3.8%). Conversely, the probability of GM 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 GM 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 GM 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, INM-N84 (92.1%) exhibited a higher probability of achieving a GM above the threshold of 100,000 Tk ha^{-1}, followed by the UDP (91.0%) treatment, for BRRI dhan67. Similarly, comparable results for GM were observed for BRRI dhan88 (Fig. 3).

<Fig. 3 here>

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.

In Kaliganj, the probability of achieving a GM 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 GM above the threshold of 100,000 Tk ha^{-1} was recorded for INM-N84 (74.7%), followed by the UDP treatment (74.5%) in BRRI dhan67. Similarly, the probability of GM above the threshold of 100,000 Tk ha^{-1} was higher for INM-N84 (6.5%) in BRRI dhan88 (Fig. 4).

<Fig. 4 here>

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.

4. Discussion

4.1. Yield and yield contributing characters

Our results showed that the combined application of organic and inorganic fertilizers as integrated nutrient management (INM) and UDP significantly increased rice yield and yield contributing characters in both rice varieties (BRRI dhan67 and BRRI dhan88) (Tables 3 and 4). The increased yield can be attributed to the decreased soil salinity (Fig. 1) and the increased tiller and panicle number, filled grain, and grain per panicle observed under the INM treatments in both locations (Tables S1 and S2). 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). Moreover, the application of cow dung and ash might be played a significant role in improving the soil permeability and leaching Na^+ from the exchange site of the soil profile by improving water movement in the soil (Leogrande and Vitti, 2019; Lee et al., 2022). Furthermore, the use of cow dung and ash may increase cation exchange capacity and ion adsorption with clay particles, hence lowering the soluble salt concentration in the soil solution. (Leogrande and Vitti, 2019). In addition to organic amendment, inorganic amendment under INM treatments might be considered an important source of Ca^{2+} to replace the exchangeable Na^+ on the exchange sites, thus improving soil fertility and enhancing crop growth in saline soils (Leogrande and Vitti, 2019; Chen et al., 2021).

UDP yielded similar results to the INM-N84 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 NH_4^+ 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 NH_4^+ (0.175 nm) is relatively higher compared to Na^+ (0.102 nm), and their charges are also similar; hence NH_4^+ 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 finding (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 Ca^{2+} to the shoot instead of Na^+. 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.

4.2. Nitrogen uptake and NUE

In general, the higher N rate showed higher total nitrogen uptake (TNU). Although farmers' practice (FP) and soil test-based (STB) fertilizers contain higher N rates, they produced lower TNU compared to the application of organic and inorganic fertilizers as INM treatments in both locations (Tables 3 and 4). Lower TNU is probably associated with the presence of a higher concentration of soluble salts (Na^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-) in saline soil, leading to ion toxicity which inhibits the metabolic process 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 TNU under INM treatments could be due to reduced soil salinity (Fig. 1) and higher total aboveground biomass (Tables 3 and 4). Combined application of organic and inorganic fertilizer 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 UDP. However, UDP and INM-N84 treatments showed similar recovery efficiency of N (RE_N) could be associated with higher grain yield and TNU (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 NH_4^+ in the rhizosphere and larger root volume, which could secret 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 NUE. 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 NUE. In contrast, there was wno significant variation in the physiological efficiency of N (PE_N) between UDP and INM-N84 treatments due to higher grain yield and TNU (Tables 3 and 4). However, our findings show that BRRI dhan67 gave a significant increase in NUE across the fertilizer treatments in both locations compared to BRRI dhan88.

4.3. CH_4 emissions

Reducing CH_4 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 CH_4 emissions in both 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 reduced redox potential, thus resulting in higher CH_4 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 increased concentration of non-exchangeable available NH_4^+-N 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). 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 to give 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).

4.4. GWP and YSE

Across the cultivars, higher GWP was observed in both INM treatments compared to other treatments due to higher cumulative CH_4 emissions (Table 5), which is consistent with previous findings (Kimani et al., 2020; Islam et al., 2022c, 2022d). In contrast, compared to other treatments, UDP treatment significantly decreased GWP and YSE by about 17-31% and 23-28%, respectively (Table 5). Lower GWP and YSE are probably linked to reduced cumulative CH_4 emissions and higher rice yields (Tables 3 and 4), which aligns with earlier reports (Islam et al., 2022c, 2022d).

BRRI dhan67 reduced GWP and YSE of CH_4 by about 4.8% 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 YSE (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.

4.5. Economic viability

Our findings suggest that BRRI dhan67, especially when combined with INM-N84 or UDP treatments, has a higher potential for achieving higher GM and better economic performance in terms of profitability compared to BRRI dhan88 in the saline coastal ecosystem of

Bangladesh. Specifically, the higher RFI and MBCR under INM-N84 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-N84 treatment, it gave higher GM resulting in higher MRR in INM treatment under both locations (Table 6). Moreover, for getting GM above the threshold of 100,000 Tk ha^{-1}, INM-N84 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-N84 and UDP treatments, at both locations (Table S3). Therefore, the UDP and INM-N84 treatments can be regarded as economically profitable technologies for BRRI dhan67 in the coastal saline zone of Bangladesh. The reasons for economic viability of the INM-N84 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

This study suggests that the combined application of organic and inorganic amendments, known as integrated nutrient management, proves to be an effective approach in reducing soil salinity while simultaneously increasing rice yield and nitrogen use efficiency (NUE) in both cultivars of BRRI dhan67 and BRRI dhan88. While comparing crop varieties, RRI dhan67, a salinity tolerant variety, showed a potential to increase rice yield and NUE, along with a higher probability of gross margin compared to BRRI dhan88, a conventional variety. Moreover, BRRI dhan67 reduced yield-scaled emission (YSE) of CH_4 by about 22% compared to BRRI dhan88. In contrast, the cost-dominant analysis excluded all fertilizer treatments except for UDP and INM-N84 treatments from both locations. Consequently, both UDP and INM-N84 treatments showed economic viability in both locations, supported by a higher marginal benefit cost ratio (MBCR) and marginal rate of return (MRR). However, the degree of increment of MRR was more in INM-N84 treatment compared to UDP treatment. Although INM-N84 significantly ($p<0.05$) increased the YSE of CH_4 by about 38% compared to UDP treatment, the increased emissions could be managed by reducing soil salinity, and higher rice yield and MRR. In conclusion, the selection of optimal rice cultivar with appropriate fertilizer management could be an effective strategy to address soil salinity, and economically profitable and sustainable rice production while ensuring low-carbon agriculture in saline soils.

However, the limitation of this study is that only two rice cultivars, BRRI dhan67 and BRRI dhan88 were selected, which may limit the applicability of the findings to other rice cultivars in the coastal saline ecosystem. Future research should aim to include a wider range of rice cultivars to enhance our understanding of their responses in such environments. Additionally, the research was conducted only in two locations of saline ecosystems (BRRI farm and Kaliganj in Satkhira), which may restrict the generalizability of the results to areas with different soil and environmental conditions. Extrapolating the research to various geographic regions with diverse soil conditions will improve the relevance and applicability of the findings. Addressing these limitations and exploring these research areas will contribute to more robust and practical recommendations for sustainable rice cultivation in coastal regions.

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References

Ali, M.N., Ghoshi, B., Gantait, S., Chakraborty, S., 2014. Selection of Rice Genotypes for Salinity Tolerance Through Morpho-Biochemical Assessment. Rice Sci. 21, 288-298. DOI: 10.1016/S1672-6308(13)60189-4.

Anderson, J.R., Dillon, J.L., 1977. Agricultural Decision Analysis. Iowa State University Press.

Angin, I., Aksakal, E.L., Sari, S., Alanyalioglu, M., 2022. Effective removal of sodium ion as efflorescence at soil surface using ammonium salts. J. Environ. Manage. 320, 115842. https://doi.org/10.1016/j.jenvman.2022.115842.

Baruah, K.K., Gogoi, B., Gogoi, P., 2010. Plant physiological and soil characteristics associated with methane and nitrous oxide emission from rice paddy. Physiol. Mol. Biol. Plants 16, 79–91. https://doi.org/10.1007/s12298-010-0010-1.

Bell, R.W., Mainuddin, M., Barrett-Lennard, E.G., Sarangi, S. K., Maniruzzaman, M., Brahmachari, K., Sarker, K.K., Burman, D., Gaydon, D.S., Kirby, J.M., Glover, M., Rashid, M.H., Khan, M.S.I., Kabir, M.E., Rahman, M.A., Hossain, M.B., 2019. Cropping systems intensification in the coastal zone of the Ganges Delta: opportunities and risks. J. Indian Soc. Coast. Agric. Res. 37,153–161.

Bodelier, P.L., Roslev, P., Henckel, T., Frenzel, P., 2000. Stimulation by ammonium based fertilizers of methane oxidation in soil around rice roots. Nature 43, 421–424.

Bustamante, M.A., Ceglie, F.G., Aly, A., Mihreteab, H.T., Ciaccia, C., Tittarelli, F., 2016. Phosphorus availability from rock phosphate: combined effect of green waste composting and sulfur addition. J. Environ. Manag. 182, 557–563. https://doi.org/10.1016/j.jenvman.2016.08.016.

Cassia, R., Nocioni, M., Correa-Aragunde, N., Lamattina, L., 2018. Climate change and the impact of greenhouse gasses: CO_2 and NO, friends and foes of plant oxidative stress. Front. Plant Sci. 9, 273. https://doi.org/10.3389/fpls.2018.00273

Chavas, J.P., Chambers, R.G., Pope, R.D., 2010. Production economics and farm management: a century of contributions. Am. J. Agricult. Econom. 92, 356–375. doi: 10.1093/ajae/aaq004

Chen, Y., Li, S., Zhang, Y., Li, T., Ge, H., Xia, S., Gu, J., Zhang, H., Lu, B., Wu, X., Wang, Z., Yang, J., Zhang, J., Liu, L., 2019. Rice root morphological and physiological traits interaction with rhizosphere soil and its effect on methane emissions in paddy fields. Soil Biol. Biochem. 129, 191-200. https://doi.org/10.1016/j.soilbio.2018.11.015.

Chen, Y., Zhang, Y., Li, S., Liu, S., Li, G., Zhang, D., Lv, B., Gu, J., Zhang, H., Yang, J., Liu, L., 2021. *OsRGA1* optimizes photosynthate allocation for roots to reduce methane emissions and improve yield in paddy ecosystems. Soil Biol. Biochem. 160, 108344. https://doi.org/10.1016/j.soilbio.2021.108344.

Ding, H., Hu, Q., Cai, M., Cao, C., Jiang, Y., 2022. Effect of dissolved organic matter (DOM) on greenhouse gas emissions in rice cultivars. Agric. Ecosyst. Environ. 330, 107870. https://doi.org/10.1016/j.agee.2022.107870.

Djaman, K., Mel, V., Boye, A., Diop, L., Manneh, B., EI-Namaky, R., Koudahe, K., Futakuchi, K., 2019. Rice genotype and fertilizer management for improving rice productivity under saline soil conditions. Paddy Water Environ. https://doi.org/10.1007/s10333-019-00763-w.

Fageria, N.K., Barbosa, F.M.P., 2001. Nitrogen use efficiency in lowland rice genotypes. Commun. Soil Sci. Plant Anal. 32, 2079–2089.

Fageria, N.K., Moreira, A., Coelho, A.M., 2011. Yield and yield components of upland rice as influenced by nitrogen sources. J. Plant Nutr. 34, 361-370. DOI: 10.1080/01904167.2011.536878.

Ghafoor, A., Murtaza, G., Rehman, M. Z., Sabir, M., 2012. Reclamation and salt leaching efficiency for tile drained saline-sodic soil using marginal quality water for irrigating rice and wheat crops. Land Degrad. Dev. 23, 1–9. https://doi.org/10.1002/ldr.1033

Ghosh, D., Brahmachari, K., Skalicky, M., Roy, D., Das, A., Sarkar, S., Moulick, D., Brestic, M., Hejnak, V., Vachova, P., Hassan, M.M., Hossain, A., 2022. The combination of organic and inorganic fertilizers influence the weed growth, productivity and soil fertility of monsoon rice. PLoS ONE 17, e0262586. https://doi.org/10.1371/journal.pone.0262586.

Gilbert, B., Frenzel, P., 1998. Rice roots and CH_4 oxidation: the activity of bacteria, their distribution and the microenvironment. Soil Biol. Biochem. 30, 1903–1916.

Habib, M.A., Islam, S.M.M., Haque, M.A., Hassan, L., Ali, M.Z., Nayak, S., Dar, M.H., Gaihre, Y.K., 2023. Effects of irrigation regimes and rice varieties on methane emissions and yield of dry season rice in Bangladesh. Soil Syst. 7, 41. https://doi.org/10.3390/soilsystems7020041

Hardaker, J., Huirne, R.B., Anderson, J.R., Lien, G., 2004. Coping With Risk in Agriculture. Wallingford: CABI. doi: 10.1079/9780851998312.0000

Islam, M.N., Bell, R.W., Barrett-Lennard, E.G., Maniruzzaman, M., 2022a. Growth and yield responses of sunflower to drainage in waterlogged saline soil are caused by changes in plant-water relations and ion concentrations in leaves. Plant Soil 479, 679–697. https://doi.org/10.1007/s11104-022-05560-9.

Islam, M.N., Bell, R.W., Barrett-Lennard, E.G., Maniruzzaman, M., 2022b. Shallow surface and subsurface drains alleviate waterlogging and salinity in a clay-textured soil and improve the yield of sunflower in the Ganges Delta. Agron. Sustain. Dev. 42, https://doi.org/10.1007/s13593-021-00746-4.

Islam, S.M.M., Gaihre, Y.K., Biswas, J.C., Jahan, M.S., Singh, U., Adhikary, S.K., Satter, M.A., Saleque, M.A., 2018. Different nitrogen rates and methods of application for dry season rice cultivation with alternate wetting and drying irrigation: Fate of nitrogen and grain yield. Agric. Water Manag. 196, 144–153. https://doi.org/10.1016/j.agwat.2017.11.002.

Islam, S.M.M., Gaihre, Y.K., Islam, M.R., Ahmed, M.N., Akter, M., Singh, U., Sander, B.O., 2022d. Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management. J. of Environ. Mgt. 307, doi.org/10.1016/j.jenvman.2022.114520.

Islam, S.M.M., Gaihre, Y.K., Islam, M.R., Akter, M., Mahmud, A.A., Singh, U., Sander, B.O., 2020. Effects of water management on greenhouse gas emissions from farmers' rice fields in Bangladesh. Sci. Total Environ. 734, 139382. https://doi.org/10.1016/j.scitotenv.2020.139382.

Islam, S.M.M., Gaihre, Y.K., Islam, M.R., Khatun, A., Islam, A., 2022c. Integrated plant nutrient systems improve rice yields without affecting greenhouse gas emissions from lowland rice cultivation. Sustainability 14, 11338. https://doi.org/10.3390/su141811338307.

Islam, S.M.M., Gaihre, Y.K., Shah, A.L., Singh, U., Sarkar, M.I.U., Satter, M.A., Sanabria, J., Biswas, J.C., 2016. Rice yields and nitrogen use efficiency with different fertilizers and water management under intensive lowland rice cropping systems in Bangladesh. Nutr. Cycl. Agroecosyst. 106, 143–156.

Ismail, A.M., Horie, T. 2017. Genomics, physiology, and molecular breeding approaches for improving salt tolerance. Annu. Rev. Plant Biol. 68, 405-434.

Kimani, S.M., Bimantara, P. O., Hattori, S., Tawaraya, K., Sudo, S., Xu, X., Cheng, W., 2020. Co-application of poultry-litter biochar with Azolla has synergistic effects on CH_4 and N_2O emissions from rice paddy soils. Heliyon, 6, e05042. https://doi.org/10.1016/j.heliyon.2020.e05042.

Lee, X., Yang, F., Xing, Y., Huang, Y., Xu, L., Liu, Z., Holtzman, R., Kan, I., Li, Y., Zhang, L., Zhou, H., 2022. Use of biochar to manage soil salts and water: Effects and mechanisms. Catena 211, 106018. https://doi.org/10.1016/j.catena.2022.106018.

Leogrande, R., Vitti, C., 2019. Use of organic amendments to reclaim saline and sodic soils: a review. Arid Land Res. Manag. 10.1080/15324982.2018.1498038.

Liang, Y.C., Yang, Y.F., Yang, C.G., Shen, Q.Q., Zhou, J.M., Yang, L.Z., 2003. Soil enzymatic activity and growth of rice and barley as influenced by organic matter in an anthropogenic soil. Geoderma 115, 149–160.

Lien, G., 2003. Assisting whole-farm decision-making through stochastic budgeting. Agricult. Syst. 76, 399–413. doi: 10.1016/S0308-521X(02)00079-3

Liu, T.Q., Fan, D.J., Zhang, X.X., Chen, J., Lia, C.F., Cao, C.G., 2015. 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, 80–90.

Liu, T.Q., Li, S.H., Guo, L.G., Cao, C.G., Li, C.F., Zhai, Z.B., Zhou, J.Y., Mei, Y.M., Ke, H.J., 2020. Advantages of nitrogen fertilizer deep placement in greenhouse gas emissions and net ecosystem economic benefits from no-tillage paddy fields. J. Clean. Prod. 263, 121322. https://doi.org/10.1016/j.jclepro.2020.121322.

Luke, C., Bodrossy, L., Lupotto, E., Frenzel, P., 2011. Methanotrophic bacteria associated to rice roots: the cultivar effect assessed by T-RFLP and microarray analysis. Environ. Microbiol. Rep. 3, 518–525.

Mao, X., Yang, Y., Guan, P., Geng, L., Ma, L., Di, H., Liu, W., Li, B., 2022. Remediation of organic amendments on soil salinization: Focusing on the relationship between soil salts and microbial communities. Ecotoxicol. Environ. Saf. 239, 113616. https://doi.org/10.1016/j.ecoenv.2022.113616.

Rahman, A.K.M.M., Ahmed, K.M., Butler, A.P., Hoque, M.A., 2018. Influence of surface geology and micro-scale land use on the shallow subsurface salinity in deltaic coastal areas: a case from southwest Bangladesh. Environ. Earth Sci. 77, https://doi.org/10.1007/s12665-018-7594-0

Rahman, M.S., Haque, M.M., Kabir, M.J., Islam, A.K.M.S., Sarkar, M.A.R., Mamun, M.A.A., Salam, M.U., Kabir, M.S., 2020. Enhancing rice Productivity in the unfavourable ecosystems of Bangladesh. Bangladesh Rice Journal, 24(2), pp.83-102. https://doi.org/10.3329/brj.v24i2.53450

Rhoades, J.D., 1996. Salinity: electrical conductivity and total dissolved solids. In: Methods of soil analysis, part 3: chemical methods, Vol. 5. Soil Science Society of America, Inc., Madison, Wisconsin, USA, pp. 417–435.

Sarkar, M.A.R., Rahman, M.C., Rahaman, M.S., Sarker, M.R., Islam, M.A., Balie, J., Kabir, M.S., 2022. Adoption determinants of exotic rice cultivars in Bangladesh. Front. Sustain. Food Syst. 6:813933. doi: 10.3389/fsufs.2022.813933

Shaygan, M., Baumgartl, T., 2022. Reclamation of salt-affected land: A review. Soil Syst. 6, 61. https://doi.org/10.3390/ soilsystems6030061.

SRDI, Soil Resources Development Institute. 2010. Saline soils of Bangladesh. http://srdi.portal.gov.bd/sites/default/files/files/srdi.portal.gov.bd/publications/bc598e7a_df21_49ee_882e_0302c974015f/Soil%20salinity%20report-Nov%202010.pdf. Accessed on 7 July 2023.

Sugiura, Y., Makita, Y., Horie, M., 2021. Ammonium-to-sodium ion-exchange process at the interlayer of octacalcium phosphate. RSC Adv. 11, 39503. DOI: 10.1039/d1ra07939e.

Sutardi., Pertiwi, M.D., Praptana, R.H., Anda, M., Purwaningsih, H., Triastono, J., Kristamtini., Susanto, U., Widyayanti, S., Kabarsih, M., Sahara, D., Malik, A., Oelviani, R., Arianti, F.D., Harsanti, E.S., Wihardjaka, A., Cempaka, I.G., Riyanto, D., Widodo, S., 2022. Increasing yield and economic value of upland rice using inorganic fertilizer and poultry manure in dryland. Agronomy 12, 2829. https://doi.org/10.3390/agronomy12112829.

van der Zee, S.E.A.T.M., Stofberg, S.F., Yang, X., Liu, Y., Islam, M.N., Hu, Y.F., 2017. Irrigation and drainage in agriculture: a salinity and environmental perspective. In: S. Kulshreshtha, Elshorbagy, A., editor Current Perspective on Irrigation and Drainage. IntechOpen, London, UK. p. 1-21. https://www.intechopen.com/chapters/52812

Walker, D.J., Bernal, M.P., 2008. The effects of olive mill waste compost and poultry manure on the availability and plant uptake of nutrients in a highly saline soil. Bioresour. Technol. 99, 396–403. https://doi.org/10.1016/j.biortech.2006.12.006

Wichern, F., Islam, M.R., Hemkemeyer, M., Watson, C., Joergensen, R.G., 2020. Organic amendments alleviate salinity effects on soil microorganisms and mineralisation processes in aerobic and anaerobic paddy rice soils. Front. Sustain. Food Syst. 4, 30. doi: 10.3389/fsufs.2020.00030.

Yaduvanshi, N.P.S., Swarup, A., 2005. Effect of continuous use of sodic irrigation water with and without gypsum, farmyard manure, pressmud and fertilizer on soil properties and yields of rice and wheat in a long-term experiment. Nutr. Cycl. Agroecosyst. 73, 111–118.

Yoshida, S., Forno, D.A., Cock, J.H., Gomez, K.A., 1976. Laboratory manual for physiological Studies of Rice, 3rd edition. International Rice Research Institute, Manila Philippines.

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_4OAc extraction
Available Na (mg kg^{-1})	1.22	0.52	CH_3COONH_4 extraction
Available Ca (cmol kg^{-1})	15.08	17.83	CH_3COONH_4 extraction
Available Mg (cmol kg^{-1})	5.56	5.46	CH_3COONH_4 extraction
Available S (mg kg^{-1})	24.09	7.12	$Ca(H_2PO_4)_2$ 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/100g soil)	22.48	24.39	-
SAR	0.38	0.15	-
Texture	Silty clay loam	Silty clay loam	Hydrometer method

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*	P	K	S	Zn
FP-N138	Farmers' practice	138	30	55	15	1.0	0	0	0	0	0	138	30	55	15	1.0
UDP-N78	Urea deep placement	78	20	70	18	2.5	0	0	0	0	0	78	20	70	18	2.5
OCP fertilizer-N110	OCP compound fertilizer	110	0	70	18	2.5	10.3	22.0	0	5.5	1.1	120	22	70	24	3.6
STB-N120	Soil test based	120	20	70	18	2.5	0	0	0	0	0	120	20	70	18	2.5
INM-N120 (100% STB + ash)	Integrated nutrient management (100% STB + 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-N84 (70% STB with ash + cow dung)	INM (70% STB 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

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

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 BRRI 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-N138	Mean	5.3cA	4.4bB	5.4b	4.4a	82.4b	69.7b	21.9d	18.0d	39.7d	31.6d	56.1b	
UDP-N78		5.9abA	4.8abB	6.2a	4.8a	82.0b	70.8b	47.2a	36.9a	69.8a	57.4a	66.0a	
OCP fertilizer-N110		5.5bcA	4.5bB	5.7ab	4.5a	92.7a	71.2b	27.6c	21.3cd	54.3c	37.6cd	53.6b	
STB-N120		5.4bcA	4.8abB	5.4b	4.6a	83.4b	72.6ab	26.3cd	23.3c	46.5d	38.8cd	59.0ab	
INM-N120 (100% STB + ash)		5.8abA	4.9abB	5.8ab	4.8a	96.8a	80.4a	29.8c	24.3c	57.7bc	45.2bc	52.5b	
INM-N84 (70% STB 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	

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, STB, INM, V1, and V2 correspond to farmers' practice, urea deep placement, soil test-based, integrated nutrient management, BRRI dhan67, and BRRI dhan88, respectively. * and ns denote significant, and non-significant at a 5% level of probability, respectively.

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-N138	Mean	4.6bA	2.7cB	4.6b	3.0b	68.6b	43.7b	18.5d	7.2d	29.9c	15.1d	55.2	
UDP-N78		5.0abA	3.1abcB	5.1ab	3.3ab	73.1b	46.9ab	37.8a	17.9a	58.7a	30.9a	61.0	
OCP fertilizer-N110		4.9abA	3.0abcB	4.8ab	3.2ab	74.2b	47.1ab	23.7c	10.8cd	39.0b	20.3cd	56.2	
STB-N120		4.8abA	2.9bcB	4.9ab	3.1ab	71.3b	47.3ab	22.8c	9.6cd	36.6b	20.4cd	54.7	
INM-N120 (100% STB + ash)		4.6bA	3.2abB	4.7b	3.4ab	72.7b	51.6a	21.3cd	12.4bc	37.8b	23.9bc	52.9	
INM-N84 (70% STB 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		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, STB, INM, V1, and V2 correspond to farmers' practice, urea deep placement, soil test-based, integrated nutrient management, BRRI dhan67, and BRRI dhan88, respectively. * and ns denote significant, and non-significant at a 5% level of probability, respectively.

Table 5. The effects of variety, fertilizer management, and year on seasonal CH_4 emissions, emission factor GWP, and YSE 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})		GWP of CH_4		YSE of CH_4	
		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-N138	Mean	144.9b		1.33b		4057.4b		30.5ab	
UDP-N78		115.8c		1.06c		3242.2c		22.1c	
STB-N120		139.6b		1.28b		3909.9b		28.5b	
INM-N120 (100% STB + ash)		160.6a		1.47a		4496.0a		30.8a	
INM-N84 (70% STB with ash + cow dung)		166.6a		1.53a		4665.9a		30.4ab	
Effects of the year (means across variety and fertilizer treatment)									
Mean	2020	149.1a		1.37a		4174.6a		31.0a	
	2021	141.9b		1.30b		3973.9b		25.9b	
Effects of variety (means across year and fertilizer treatment)									
		BRRI dhan67	BRRI dhan88	BRRI dhan67	BRRI dhan88	BRRI dhan67	BRRI dhan88	BRRI dhan67	BRRI dhan88
Mean	Mean	141.9B	149.2A	1.30B	1.37A	3972.3B	4176.3A	25.0B	31.9A
ANOVA (p values)									
Fertilizer (F)		*		*		*		*	
Variety (V)		*		*		*		*	
Year (Y)		ns		ns		ns		ns	
F × V		ns		ns		ns		ns	
F × Y		ns		ns		ns		ns	
V × Y		ns		ns		ns		*	
F × V × Y		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 Tukeys's honest significant difference (HSD) test. FP, UDP, STB, and INM correspond to farmers' practice, urea deep placement, soil test-based, and integrated nutrient management, 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-N138	18574	18574	175200	145200	156626	126626	9.43	7.82	12.20	9.44
UDP-N78	17557	17557	195600	158400	178043	140843	11.14	9.02	16.65	12.54
OCP fertilizer-N110	17582	17582	182100	148500	164518	130918	10.36	8.45	14.77	11.16
STB-N120	18018	18018	178200	151800	160182	133782	9.89	8.43	13.45	10.96
INM-N120 (100% STB + ash)	21018	21018	191400	161400	170382	140382	9.11	7.68	10.94	8.81
INM-N84 (70% STB with ash + cow dung)	18000	18000	204300	171000	186300	153000	11.35	9.50	16.82	13.44
N control	10187	10187	72900	66000	62713	55813	7.16	6.48	-	-
Average	17277	17277	171386	143186	154109	125909	9.78	8.20	14.14	11.06
Kaliganj, Satkhira										
FP-N138	18574	18574	151800	90000	133226	71426	8.17	4.85	10.19	4.01
UDP-N78	17557	17557	165300	102900	147743	85343	9.42	5.86	13.43	6.31
OCP fertilizer-N110	17582	17582	161400	99600	143818	82018	9.18	5.66	12.86	5.84
STB-N120	18018	18018	158700	96300	140682	78282	8.81	5.34	11.80	5.10
INM-N120 (100% STB + ash)	21018	21018	152100	106200	131082	85182	7.24	5.05	7.92	4.60
INM-N84 (70% STB with ash + cow dung)	18000	18000	171900	112500	153900	94500	9.55	6.25	13.52	7.18
N control	10187	10187	66300	56400	56113	46213	6.51	5.54	-	-
Average	17277	17277	146786	94843	129509	77566	8.41	5.51	11.62	5.51

FP, UDP, RF, INM, Tk, and MBCR correspond to farmers' practice, urea deep placement, recommended fertilizer, integrated nutrient management, Bangladeshi currency in Taka, and marginal benefit-cost ratio, respectively.

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						
10187	N control	BRRI dhan67	62713	-	-	-
17557	UDP-N78	BRRI dhan67	178043	7370	115330	1565
18000	INM-N84 (70% STB with ash + cow dung)	BRRI dhan67	186300	443	8257	1864
Kaliganj, Satkhira						
10187	N control	BRRI dhan67	56113	–	–	–
17557	UDP-N78	BRRI dhan67	147743	7370	91630	1243
18000	INM-N84 (70% STB with ash + cow dung)	BRRI dhan67	153900	443	6157	1390