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Reclamation of Coastal Soil Salinity towards Sustainable Rice Production and Mitigating Global Warming Potentials in the Changing Climate

Muhammad Aslam Ali*, Md. Ashraful Islam Khan, Md. Abdul Baten, Hafsa Jahan Hiya, Murad Ahmed Farukh, Shuvo Kumar Sarkar

Department of Environmental Science, Bangladesh Agricultural University, Mymensingh, Bangladesh
Email: *aslam.envs@bau.edu.bd, baten_envsc@yahoo.com, hafsa_envsc@bau.edu.bd, farukh_envsc@bau.edu.bd, Kabul_bau@yahoo.com, sarkarshuvo.just@gmail.com

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Abstract

Soil salinity has become a major constraint to rice productivity in the coastal region of Bangladesh, which threatened food security. Therefore, field experiment was conducted at salt stressed Shyamnagor Upazilla of Satkhira district to improve the soil salinity status, sustainable rice production and suppression of global warming potentials. Selected soil amendments viz. trichocompost, tea waste compost, azolla compost and phospho-gypsum (PG) were applied in the field plots one week prior to rice transplanting. In addition, proline solution (25 mM) was applied on the transplanted rice plants at active vegetative stage. Gas samples from the paddy field were collected by Closed Chamber technique and analyzed in by Gas Chromatograph. The 25% replacement of chemical fertilizer (i.e., 75% NPKS) with trichocompost, tea waste compost, Azolla compost and Phospho-gypsum amendments increased grain yield by 4.7% - 7.0%, 2.3% - 7.1% 11.9% - 16.6% and 9.5% - 14.2% during dry boro rice cultivation, while grain yield increments of 5.0% - 7.6%, 2.3% - 10.2%, 12.8% - 15.3% and 10.2% - 15.3% were recorded in wet Aman season respectively, compared to chemically fertilized (100% NPKS) field plot. The least GWPs 3575 and 3650 kg CO_2 eq./ha were found in PG Cyanobacterial mixture with proline (T10) and tea waste compost with proline (T8) amended rice field, while the maximum GWPs 4725 and 4500 kg CO_2 eq./ha were recorded in NPKS fertilized (100%, T2) and NPKS (75%) with Azolla compost (T5) amended plots during dry boro rice cultivation. The overall soil properties improved significantly with the selected soil amendments, while soil electrical conductivity (EC), soil pH and Na^+ cation in the amended soil decreased, eventually improved the soil salinity status. Conclusively, phospho-gypsum amendments with cyanobacteria inoculation and proline solution (25 mM) application could be an effective option to reclaim coastal saline soils, sustaining rice productivity and reducing global warming potentials.

Keywords

Coastal Paddy, Soil Salinity, Global Warming, Phospho-Gypsum, Cyanobacteria, Proline

1. Introduction

Climate change has been affecting coastal agriculture through sea level rise and saline water intrusion in coastal cultivable land. Salinity is a major threat to crop productivity in the south-western part of Bangladesh. Salinity affected coastal area of Bangladesh covers about 30% of the arable land, which covers about 53% of the net cultivable area in coastal districts (Haque, 2006). Generally, soils with high levels of soluble salts (saline soil) and exchangeable sodium (alkali soil) are considered salt-affected soils. Saline soils contain high concentration of salts mainly chlorides and sulfate of sodium, calcium and magnesium. Additional features of saline soil are electrical conductivity EC value greater than 4 $dS\cdot m^{-1}$, pH value greater than 7.0, ESP value less than 15 and Sodium absorption ratio (SAR) less than 13 (McGeorge, 1954). In Bangladesh, the majority of the saline land (0.65 million ha) exists in the districts of Satkhira, Khulna, Bagerhat, Barguna, Patuakhali, Pirojpur and Bhola, while a smaller portion (0.18 million ha) in the districts of Chittagong, Cox's Bazar, Noakhali, Lakshmipur, Feni and Chandpur. Salinity degrades soil fertility, creates adverse environment in soil, which restricts plant growth, development and yield of crops. Salinity stress is caused from the accumulation of soluble salts in the root zone of plants causing their growth retardation, hormonal imbalance, and oxidative stress initiation. Therefore, exogenous inputs (organic, inorganic and biological agents) application may contribute to improve salinity stress in agricultural productivity. Plant growth-promoting rhizobacteria or arbuscular mycorrhizae in rhizosphere may develop plant tolerance to withstand severe salinity by producing growth-promoting hormones and absorbing more nutrients. In addition, organic and inorganic soil amendments might be effective in mitigating soil salinity by improving soil physicochemical properties and nutrients supplement. Furthermore, exogenous plant hormones may improve plant growth, reproductive development, phyto-morphogenesis, and defense against salt stresses.

Nowadays the intensity of natural disasters such as cyclones, sea level rise, tidal surges and flood occcurrence increased which caused salt water intrusion in agricultural field, thereby developed intense soil salinity. Consequently, the cropping area is reducing and cultivation of *Aus*, *Aman*, *Boro* and other rabi (dry season) crops are being restricted. The major inhibitory effect of salinity on rice plant growth and yield has been attributed to osmotic effect, ion toxicity and nutritional imbalance leading to reduction in photosynthetic efficiency, thereby results in decreased crop production.

Salinity reclamation is a continuous process which needs time and adequate soluble Ca rich materials to remove Na from the soil below root zone as well as rebuild soil structure. Different amendments such as gypsum or phosphogypsum, sulphur containing salts etc. may be used for reclamation of saline soils. The use of gypsum as a source of Ca^{2+} is effective practice for the amelioration and management of sodium saturated soils. Gypsum may increase the availability of Ca, Mg, K, P, Fe and Mn. Phospho-gypsum, a by-product of phosphate fertilizer manufacturing industry, contains over 90% of $CaSO_4$ $2H_2O$ could be a good soil amendment to supplement mainly calcium (Ca) and sulfur (S) for rice cultivation. The high content of sulfate in gypsum will act as electron acceptor and might suppress methanogenesis by accelerating the activity of sulfate reducing bacteria for the common substrates (Ali et al., 2009). Irrigation with saline water induces changes in soil structure and adversely affects the microbe-mediated soil processes (Yan et al., 2015). Generally, the excess salt in soils restricts the microbial population and their activity through osmotic stress and inhibits the soil organic matter decomposition through alteration of microbial activities (Wang et al., 2020).

CH_4 emission must be reduced by 15% - 20% from that of 1990 levels to stabilize the GHGs concentration in the atmosphere (Watson et al., 1995). In regards to this situation, there is no alternative but to add organic amendments, inorganic fertilizers and biological amendments in the coastal saline soils of Bangladesh to ameliorate salt stress for agricultural crop production.

Cyanobacteria are important biotic components of the wetland paddy ecosystem, commonly found as floating assemblages (a water fern harbouring a cyanobacterium, *Anabaena azollae*) in rice paddies (Singh, 1977, 1979). It has been recognized that the application of Azolla cyanobacteria in combination with chemical fertilizers is a cost effective strategy for soil reclamation, sustaining rice productivity and reducing CH_4 emission (Prasanna et al., 2002, Ali et al., 2012). In the present context of Bangladesh, there are no specific research findings available in regards to restoring soil fertility, sustaining rice productivity and suppressing CH_4 emissions from the coastal paddy fields. Therefore, soil amendments with trichocompost, a trichoderma based compost fertilizer, could be one of the best organic fertilizers to rejuvenate saline soils since it is a rich source of both plant nutrients and organic matter. Tricho-compost mainly contains about 24% organic carbon, 1.2% T-N, 98 ppm Fe and 1.1% S. Tea waste is another feasible byproduct from the Tea processing industry, which may be used in combination with Trichodermal suspension. Tea waste compost mainly contains organic C 21%, T-N 1.2%, S 9.7% and Fe 35 ppm. Furthermore, proline, a compatible solute that occurs in a wide variety of plants, may contribute to the osmotic adjustment as well as to the protection of membranes, proteins and enzymes from the damaging effects of various stresses. Under salt stress, exogenous application of proline up-regulates stress-protective proteins and reduces lipid peroxidation and protein oxidation. Proline also suppresses production of free radicals and reactive oxygen species (ROS)) to overcome abiotic stresses (Hong, et al. 2000). Therefore, this research programme was undertaken to investigate the feasibility of soil amendments with reduced amount of chemical fertilization alongwith cyanobacteria proline application in coastal paddy soil salinity reclamation, sustaining rice productivity as well as mitigation of GWPs during wet aman and dry boro season rice cultivation.

2. Materials and Methods

Field Experiment setup: layout, design, treatments and activities

Field experiment was conducted at Shyamnagar Upazilla of Satkhira district from December 2019 to June 2020. The experiment was designed with Randomized Complete Block Design (RCBD), having ten (10) treatments, each replicated 3 times. There were thirty (30) plots, each unit area 10 m^2. The rice cultivar BRRI Dhan-47 was cultivated in boro season, while BRRI Dhan 73 was cultivated in Aman season. The selected soil amendments such as tricho compost, tea waste compost, azolla compost and Phospho-gypsum (PG) were applied at 5.0 $t \cdot ha^{-1}$ in the rice field one week before rice transplanting. The basal fertilizer was applied at N:P:K:S = 100:30:80:10 $kg \cdot ha^{-1}$. The composition of soil amendments used in this experiment is mentioned in **Table 1**. The experimental treatments were T1: No NPKS + No soil amendments, T_2: Farmers practice (100% NPKS, RFD) + No soil amendments, T3: NPKS (75% recommended NPKS, RFD) + Trichocompost, T4: NPKS (75% recommended doze, RFD) + Tea waste compost, T_5: NPKS (75%) + Azolla compost with Cyanobacteria, T6: NPKS (75%)+ Phospho-gypsum (PG) T7: NPKS (75%) + Trichocompost + Proline, T8: NPKS (75%) + Tea waste compost + Proline T9: NPKS (75%) + Azolla compost Cyanobacteria + Proline, T10: NPKS (75%)+ Phospho-gypsum (PG) + Proline.

Table 1. Composition of different soil amendments used in this experiment.

Nutrients	Trichocompost	Tea waste compost	Azolla compost	Phosphogypsum
pH (1:5 H_2O)	8.6	6.9	7.5	3.5
Organic C (%)	24	27	44	-
Total N (%)	1.1	1.6	4.8	-
C/N	21	17	9	-
P_2O_5 (%)	0.87	0.75	0.50	0.83
K_2O %)	1.2	1.1	3.5	
S (%)	1.1	9.7	1.7	36
Mn (%)	0.86	0.9	0.16	0.97
Fe (ppm)	98	270	2600	350
Ca (%)	0.35	0.23	0.7	30

Gas sampling, analysis and estimation of CH_4 emission

A closed-chamber method was used to estimate CH_4 emission during rice cultivation. Gas samples were collected by 50 ml gas-tight syringes at 0, 15 and 30 minutes after chamber placement over flooded plots at different rice growth stages to get average CH_4 emissions. The dimension of closed chamber was 62 cm × 62 cm × 112 cm. Samples were analyzed to determine CH_4 concentration by gas chromatograph (Shimadzu, GC 2014, Japan) with a Flame Ionization Detector. The temperatures of column, injector and detector were adjusted at 100˚C, 200˚C and 200˚C, respectively. A closed-chamber equation (Rolston, 1986) was used to estimate methane fluxes for every treatment.

$$F = \rho \times V/A \times \Delta c/\Delta t \times 273/T$$

where, F (Flux) = CH_4 emission rate (mg CH_4 m^{-2} hr^{-1}), ρ = gas density (0.714 $mg \cdot cm^{-3}$), V = volume of chamber ($A \times h$; m^3), A = surface area of chamber (length × width; m^2), h = height of the chamber (m), $\Delta c/\Delta t$ = rate of increase of CH_4gas concentration ($mg \cdot m^{-3} \cdot hr^{-1}$), T (absolute temperature) = 273 + mean temperature (˚C). Total methane flux for the entire cropping period were computed by the formula (Singh et al., 1999): Total CH_4 flux = $\sum_{i=1}^{n}(Ri \times Di)$, where, Ri = rate of methane flux ($g \cdot m^{-2} \cdot d^{-1}$) in the ith sampling interval, and n = number of sampling intervals.

Estimation of GWP

To estimate the GWP, CO_2 is typically taken as the reference gas, and an increase or reduction in emission of CH_4 is converted into "CO_2-equivalents" by means of their GWPs. In this study, we used the IPCC factors to calculate the combined GWP for 100 years (GWP = 25 × CH_4, kgCO_2-equivalents ha^{-1}) from CH_4 under various agricultural practices. In addition, the greenhouse gas intensity (GHGI) was calculated by dividing GWP by grain yield for rice.

Investigation of soil and water properties

Soil redox potential (Eh), flood water pH, EC, TDS, iron conc. and DO conc. were measured at every week interval during rice cultivation. After rice harvesting, soil organic carbon (Walkley and Black method; Allison 1965), total-**N %** (Micro-Kjeldahl method, Keeney and Nelson, 1982), available P (Colorimetric method, Watanabe and Olsen, 1985) and available S (by the calcium chloride (0.15%) extraction method were determined following standard methods. Exchangeable calcium (Ca), sodium (Na) and potassium (K) were extracted from soil using 1M CH_3COONH_4 solution (Jackson and Barak, 2005) and their concentrations in the extract were directly determined by Flame photometer (FP 902-5 PG Instrument). Exchangeable magnesium was extracted by Diethylene Tri amine Penta Acetate (DTPA) solution and its concentration in the extract was determined directly by an Atomic absorption spectrophotometer (ASS). To analyze ammonium and nitrate in water samples, the samples were filtered with 0.45 μm filter papers. Ammonium (NH_4^+) concentration in water samples were determined by Indophenol blue method (A sample volume of 25 ml was transferred into a 50-ml Erlenmeyer flask, then 1 ml phenol solution, 1 ml sodium nitroprusside solution and 2.5 ml oxidizing solution were added with thorough mixing after each addition. The samples were covered with parafilm and kept in the dark at room temperature for at least 1 h. The absorbance was measured at 640 nm using a UV spectrophotometer (UV-VI Mini 1240, Shimadzu Corporation, and Kyoto, Japan). NO_3^- concentration in water samples was determined at 410 nm using a UV spectrophotometer (Brucine-sulfanilic acid method, Jenkins & Medsken, 1964). Water soluble iron concentrations in fresh soil samples were determined by 1, 10-Phenanthroline method (Loeppert & Inskeep, 1996). Soil SAR is a measure of the ratio of sodium (Na^+) relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the water extract (solution phase) from a saturated soil paste.

Investigation rice plant growth, yield components and grain yield

Rice growth and yield characteristics were recorded under different treatments and seasons. Rice plant growth parameters such as tiller number, leaf area, leaf area index, and root volume were investigated at different growth stages. Yield components such as panicle number per hill, number of grains per panicle, ripened grains, 1000 grain weight and harvest index were determined at the harvesting stage. Grain yield and straw yield per unit area were recorded after harvest.

Rice growth, yield, soil properties and CH_4 emission data were analyzed through standard methods. Fisher's protected least significant difference (LSD) was calculated at the 0.05 probability level for making treatment mean comparisons.

3. Results and Discussion

CH_4 flux measured after rice transplanting was low, which increased gradually with plant growth and the development of soil reductive condition. It was observed that CH_4 emission rates were higher in non-amended plots (treatments T_2, T_1) compared to the soil amended plots T3, T4, T5, T6, T7, T8, T9 and T10 treatments (**Figure 1**).

The highest CH_4 peak was observed at 77 days after rice transplanting of rice plant. Among the treatments, phosphogypsum and tea waste compost amendments alongwith proline application were found effective in decreasing CH_4 emission rate (**Figure 1**).

The soil redox potential values decreased sharply in all treatments after 3 weeks of rice transplanting and sharply dropped towards −250 mV (**Figure 2**) which caused significant CH_4 emissions from rice rhizosphere to the atmosphere. However, tea waste and phospho-gypsum amendments alongwith proline application significantly decreased seasonal cumulative CH_4 emission, which may be due to higher availability of sulfate and dissolved iron concentrations, being acted as electron acceptors.

Soil amendments with PG, trichocompost and tea waste alongwith proline application improved soil redox status to some extent.

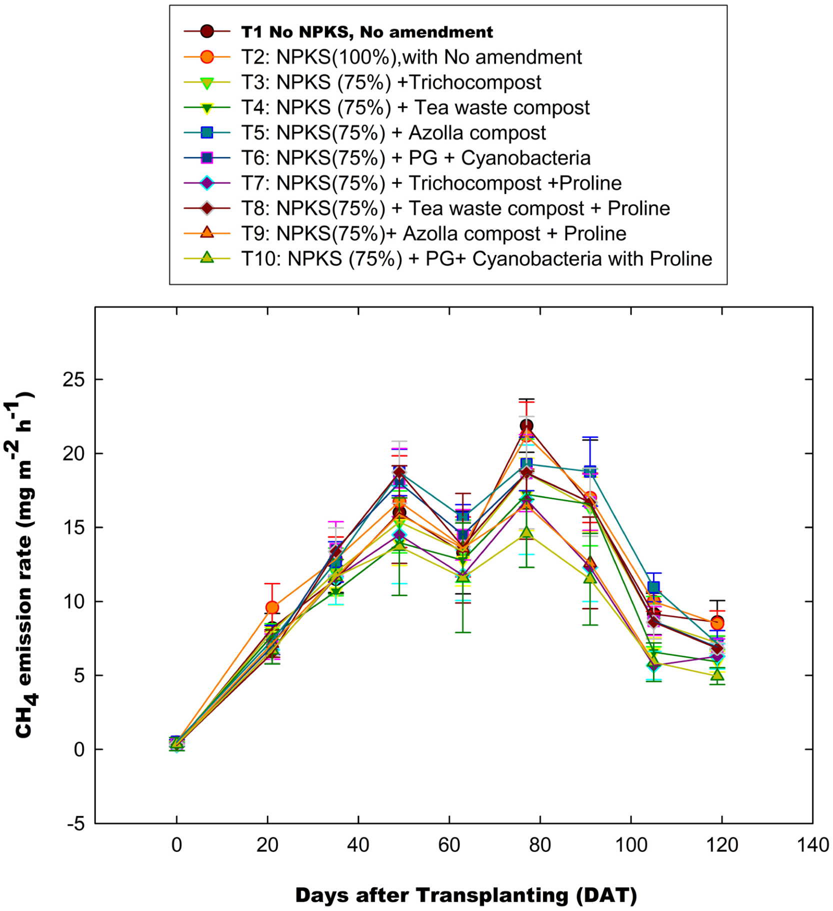

Figure 1. Trends of methane emission rate during rice cultivation.

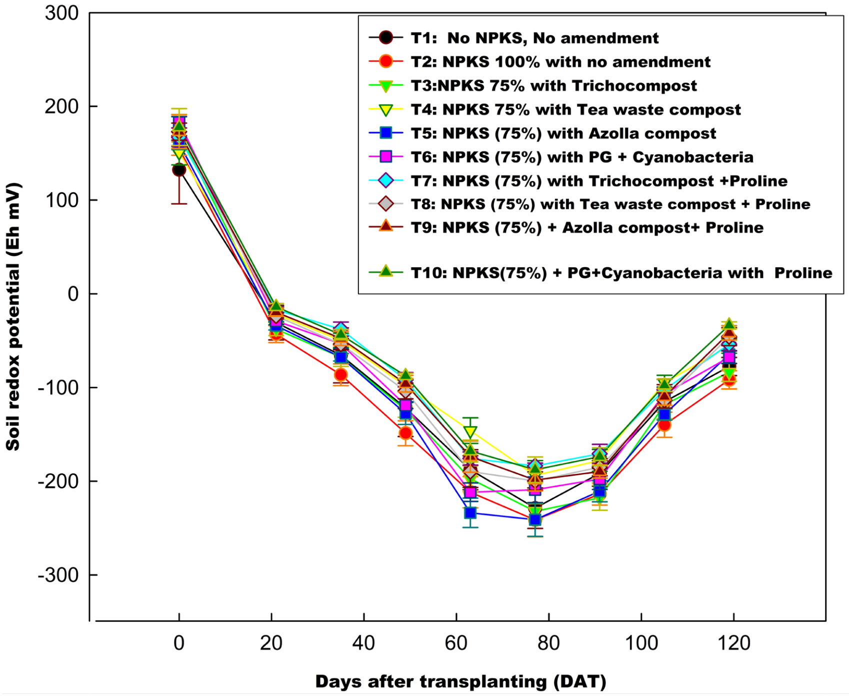

Figure 2. Trends of soil redox potential under different soil amendments.

Rice grain yield increased significantly with Azolla compost, Phospho-gypsum cyanobacteria, trichocompost and tea waste compost amendments (**Table 2**).

In the dry boro season, the maximum rice grain yield was found 4900 kg/ha in Azolla compost amended and proline applied field plots (treatment T9) followed by 4800 kg/ha in Phospho-gypsum amendments with cyanobacteria and proline application (T10), while the least cumulative seasonal CH_4 flux was recorded 143 kg CH_4/ha/season, GWPs 3575 kg CO_2 eq. ha^{-1} and GHGI (0.029 kg. Among the treatments Azolla compost + NPKS (T5), PG with NPKS (T6), Trichocompost with proline (T7), Tea waste compost with proline (T8), combined application of Azolla compost + Proline + NPKS (T9) and Phospho-gypsum amendments with proline application (T10) showed the satisfactory yield performance (4500 - 4900 kg/ha) although seasonal cumulative CH_4 emission, GWPs and GHGI were found minimum in PG and Tea waste amendments along with proline application (T10 and T8 treatments). The maximum total seasonal CH_4 fluxes were recorded (185 kg CH_4/ha) in 100% NPKS fertilized without any amendments (T2), whereas the minimum CH_4 flux (143 - 145 kg/ha) was recorded in Phospho-gypsum amendments with proline application (T10) and T8 (NPKS 75% + Tea waste compost+ Proline) treatments (**Table 2**). The 25% replacement of chemical fertilizer (NPKS) with soil amendments such as trichocompost (T3), teawaste compost (T4), Azolla compost (T5) and Phospho-gypsum (T6) increased grain yield by 4.7%, 2.3%, 11.9% and 9.5% compared to chemically fertilized plot (4200 kg/ha, in T2). Furthermore, the application of proline with soil amendments increased grain yield by 7.1%, 7.1%, 16.6% and 14.2% in Trichocompost amendment with proline(T7), Tea waste compost with proline (T8), Azolla compost with proline (T9) and PG amendments with proline (T10) respectively, compared to chemically fertilized (100% NPKS, T2) treatment.

Rice grain yield increments of 5.0% - 7.6%, 2.3% - 10.2%, 12.8% - 15.3% and 10.2% - 15.3% were also recorded in wet Aman season compared to chemically fertilized T2 (100% NPKS) treatment with trichocompost, tea waste compost, Azolla compost and Phospho-gypsum amendments respectively. The maximum GWPs were recorded 4725 and 4500 kg CO_2 eq./ha in treatments NPKS fertilized (T2) and NPKS (75%) with Azolla compost (T5) amended plots; while least GWPs were found 3575 and 3650 kg CO_2 eq./ha from PG with proline (T10) and tea waste compost with proline (T8) amended rice field plots during dry boro rice cultivation. The similar performance of Phospho-gypsum (PG) and Tea waste compost amendments were also observed on reducing GWPs from rice field in wet aman season

Effect of soil amendments and NPKS fertilization with proline application on paddy ecosystem and soil properties

Soil amendments with trichocompost, teawaste compost, Azolla compost and Phospho-gypsum significantly improved soil redox status (Eh), soil organic matter, T-N, available P, available S, exchangeable Ca^{2+} and exchangeable K^+ in soil after rice harvest, however decreased soil electrical conductivity (EC), exchangeable Na^+ content and soil pH (**Table 3**).

Table 2. Rice yield and productivity, BCR, cumulative CH_4 flux, Global warming potentials and greenhouse gas intensity (GHGI) under different soil amendments with chemical fertilizers.

Rice growing seasons (A)	Treatments (B) Recommend NPKS fertilizers with soil amendments	Grain yield (kg·ha^{-1})	Nutrients uptake by rice plant (kg/ha/season)			Gross return (Tk·ha^{-1})	Total variable cost (Tk·ha^{-1})	BCR	Cumulative CH_4 flux (kg ha^{-1} season^{-1})	GWP (kg CO_2 eq.ha^{-1})	GHGI (kg CH_4/kg grain yield)
			N	P	K						
Dry season (Boro Rice cultivation)	T1: (No NPKS, No amendments)	1000	36	8	20	49,000	55,000	0.89	171.0	4300	0.171
	T2: NPKS (100%) + No amendments	**4200**	105	12	95	105,000	83,500	**1.25**	180.0	**4500**	0.042
	T3: NPKS (75% RFD) + Trichocompost	4400	135	15	105	109,500	85,500	1.28	175.0	4375	0.038
	T4: NPKS (75% RFD) + Tea waste compost	4300	130	10	108	102,000	84,000	1.21	163.0	4050	0.035
	T5: NPKS (75% RFD) + Azolla compost	**4700**	150	18	126	128,500	87,000	**1.47**	**185.0**	**4725**	0.039
	T6: NPKS (75% RFD) + Phosphogypsum (PG)	4600	146	16	135	125,500	93,500	1.34	**155.0**	3875	0.031
	T7: NPKS (75%) + Trichocompost + Proline	4500	142	17	128	127,000	97,500	1.30	169.0	4200	0.035
	T8: NPKS (75%) + Tea waste compost + Proline	4500	150	16	125	120,000	95,000	**1.26**	**145.0**	**3650**	0.032
	T9: NPKS (75% RFD) + Azolla compost + Proline	**4900**	164	22	140	136,000	97,500	1.39	**173.0**	4350	0.035
	T10: NPKS (75% RFD) +PG + Proline	4800	160	24	138	128,000	98,000	1.30	**143.0**	**3575**	**0.029**
Wet season (Rainfed aman rice cultivation)	T1: (No NPKS, No amendments)	1200	40	10	22	56,500	53,500	1.05	151.0	3775	0.125
	T2: NPKS (100%) + No amendments	**3900**	95	14	78	110,000	86,000	1.28	169.0	**4225**	0.043
	T3: NPKS(75% RFD) + Trichocompost	4100	110	17	84	120,500	90,500	1.33	160.0	4000	0.039
	T4: NPKS (75% RFD) + Tea waste compost	4000	108	16	85	108,500	89,500	1.21	**145.0**	3625	0.038
	T5: NPKS (75% RFD) +Azolla compost	4400	118	18	94	124,500	92,500	1.34	173.0	**4325**	0.038
	T6: NPKS (75% RFD) + Phosphogypsum (PG)	4300	110	17	90	120,500	93,000	1.29	**141.0**	3525	0.032
	T7: NPKS (75%) + Trichocompost + Proline	4200	116	18	95	118,000	95,000	1.24	155.0	3875	0.037
	T8: NPKS (75%) + Tea waste compost + Proline	4300	115	16	96	115,000	94,000	1.22	**135.0**	3387	0.034
	T9: NPKS (75% RFD) + Azolla compost + Proline	4500	124	18	102	127,000	95,000	1.33	159.0	4145	0.035
	T10: NPKS (75% RFD) + PG + Proline	4500	118	17	98	125,000	97,000	1.28	**130.0**	3262	0.029
ANOVA	A	ns	*	ns	*	*	*	*	*	*	*
	B	*	*	*	*	**	**	*	*	**	*
	A × B	ns	*	*	*	*	*	*	*	*	*

Note. ns means not significant, * and * * indicate significant at 5%, and 1%, respectively.

The post harvest soil properties such as soil organic matter content in soil, available P, available S, exchangeable Ca^{2+}, and K^+ cations concentrations were increased with PG, tea waste compost, trichocompost and Azolla compost

Table 3. Post harvest soil properties under different soil amendments with chemical fertilizers (after two seasons of cropping).

Treatments Recommend NPKS fertilizers with soil amendments	Soil pH (1:5 with H_2O)	EC (dS/m)	OM (%)	T-N (%)	Av-P (ppm)	Av. S (ppm)	Exchangeable cations (meq./100 g)			Water soluble Fe (mg/kg)	Water soluble SO_4^{2-} (mg/kg)	Na^+/K^+	Na^+/Ca^{2+}
							Ca	K	Na				
T1: (No NPKS, No amendments)	7.8	7.6	1.6	0.11	29.8	14.6	1.9	0.61	4.9	0.95	21.5	8.03	2.57
T2: NPKS (100% + No amendments	7.7	7.5	1.9	0.41	31.6	20.5	2.5	1.45	4.7	1.6	25.6	3.24	1.88
T3: NPKS (75%) + Trichocompost	7.6	6.7	2.5	0.49	33.5	23.6	3.3	1.87	4.3	2.5	30.5	3.0	1.30
T4: NPKS (75%) + Tea waste compost	7.2	6.5	2.3	0.55	35.6	28.3	3.5	1.70	4.4	3.30	41.7	2.58	1.23
T5: NPKS (75%) + Azolla compost	7.7	6.6	2.7	0.63	36.5	27.6	3.7	2.25	4.7	3.15	39.8	2.0	1.27
T6: NPKS (75%) + Phosphogypsum (PG)	7.3	6.3	2.0	0.48	35.6	29.5	4.5	1.89	4.1	2.9	45.6	2.16	0.91
T7: NPKS (75%) + Trichocompost + Proline	7.5	6.2	2.6	0.57	37.5	25.7	3.6	2.17	4.5	2.8	37.3	2.07	1.25
T8 NPKS (75%) + Tea wastecompost + Proline	7.1	6.1	2.5	0.59	36.7	30.6	3.8	2.10	4.3	3.35	45.7	2.05	1.13
T9 NPKS (75% + Azolla compost + Proline	7.5	6.3	2.8	0.68	38.6	29.8	3.9	2.36	4.6	3.45	43.6	1.95	1.18
T10 NPKS (75%) + PG + Proline	7.2	6.2	2.2	0.57	36.9	31.3	4.8	1.95	4.0	3.30	49.5	2.05	0.83
LSD$_{0.05}$	0.25	0.10	0.30	0.12	2.6	2.3	0.8	0.25	0.20	0.15	4.5	0.20	0.25
Level of significance	NS	*	*	*	*	**	**	**	*	**	***	**	**

Note. ns means not significant, * and * * indicate significant at 5%, and 1%, respectively.

amendments. The soil organic matter contents 2.5% - 2.6% and 2.7% - 2.8% were recorded in the trichocompost and Azolla compost amended field soils (**Table 3**). The available P and available S, water soluble iron and sulfate concentrations were increased significantly with PG, teawaste compost and Azolla compost amendments. The higher EC value 7.6 dS/m and 7.5 dS/m were recorded in the non-amended field plots, which were significantly decreased with PG and tea waste compost amendments.

The concentration of Na was decreased significantly with PG, trichocompost and Tea waste amendments. The ratio of Na^+/K^+ and Na^+/Ca^{2+} values decreased with PG and teawaste amendments. Soil pH and EC values gradually decreased with PG amendments and tea waste amendments in field plots. The exchangeable cations such as calcium (Ca^{2+}), potassium (K^+) and sodium (Na^+) showed significant variation due to PG amendments. The highest exchangeable Ca^{2+} content was found 4.5 - 4.8 meq/100 g soil in the PG amended soil followed by 3.7 - 3.9 meq/100 g soil in Azolla compost, while the lowest value 1.9 meq/100 g was recorded in control treatment (T1). The higher exchangeable potassium (K^+)

Table 4. Correlation of seasonal cumulative CH_4 flux with rice yield and soil properties.

Parameters	Correlation co-efficient (r)
Rice grain and straw yield	
Grain yield	0.572*
Straw yield	0.548*
Soil properties	
Electrical conductivity (EC)	−0.465*
Soil pH	−0.565*
Soil Eh	−0.646**
Exchangeable K	−0.768**
Exchangeable Ca	−0.846***
Exchangeable Na	−0.658**
Water soluble Fe	−0.354**
Water soluble SO_4^{2-}	−0.789***

contents 2.25 - 2.36 meq/100 g, 1.87 - 2.17 meq/100 g and 1.89 - 2.10 meq/100 g soil were recorded in Azolla compost, Trichocompost, and the PG amended soil compared to control treatment (T1) 0.61 meq/100 g soil. The exchangeable sodium (Na^+) was found 4.9 meq/100 g soil in the control treatment (T1), which decreased towards 4.0 with PG amendments. Khatun et al., (2021) also reported similar findings with organic and PG amendments in saline soils. Gypsum, being source of Ca, might have replaced Na from soil. The fine gypsum particles as a source of soluble Ca might have reacted more quickly to replace Na from clay particles by forming sodium sulfate, which leached out of the soil profile. The flood water pH significantly ($P < 0.001$) increased with time, probably due to release of base cations such as Ca^{2+} from the applied amendment, which supports our previous findings (Khatun et al. 2021). This study also showed that there were positive correlations between total seasonal CH_4 fluxes and grain yield, however, negative correlations were also recorded with soil EC, soil, pH, soil Eh, exchangeable Na, exchangeable Ca, water soluble iron and sulfate (**Table 4**).

4. Discussion

Soil salinity causes detrimental effects on soil physico-chemical and biological properties. High salinity levels also pose a negative impact on the abundance and distribution of soil microbes and soil-dwelling organisms. Soil salinity may influence CH_4 emission from wetland rice fields (Bachelet & Neue, 1993, Lim et al., 2013, Khatun et al., 2021), which is a great concern in salt affected coastal areas. A decrease in N_2O (Jia et al., 2020), CH_4 (Marton et al., 2012, Khatun et al. 2021), and CO_2 (Reddy & Crohn, 2014, Ghosh et al., 2017) emissions are reported with increased salinity levels. However, contrasting reports on GHGs emissions are also available.

In this study, CH_4 peak observed at flowering to reproductive stages of rice growth (77 DAT), due to intense soil reduced conditions, e.g., Eh value −200 mV to −240 mV and the availability of labile organic carbon in the rice rhizosphere, which might have enhanced methanogens' activity. However, the applied soil amendments phosphogypsum (PG) with cyanobacteria, tea waste compost and trichocompost decreased seasonal cumulative CH_4 emissions significantly ($P < 0.001$) by releasing large amount of water soluble sulfate, dissolved iron (TDFe) and free iron oxides, which acted as oxidizing agents and electron acceptors, thereby, reduced CH_4 emissions during the rice cultivation. These findings are supported by Jackel and Schnell (2000). Ali et al. (2012) also reported that silicate slag, phospho-gypsum and sulfate of ammonia amendments significantly ($P < 0.05$) increased soil porosity and improved soil redox potential (Eh) status compared to that of control plot.

In this study, soil amendments with Phospho-gypsum cyanobacteria, tea waste compost, azolla compost and trichocompost significantly improved soil properties by releasing large amount of cations such as Ca^{2+}, K^{+}, and S, which replaced Na^{+} ions from the clay particles or exchangeable sites. Once Na^{+} is displaced from soil exchange sites, it may be leached out below the rooting zone, ultimately soil structural aggregation and soil porosity will be enhanced. It was found that gypsum application in combination with calcium chloride, farm manure improved the soil chemical properties by reducing the soil pH from 9.2 to 8.1, electrical conductivity from 6.35 dS/m to 2.65 dS/m and sodium adsorption ratio from 26.5 to 11.6, while increased paddy yield from 695.7 kg/ha to 1644 kg/ha (Shaaban et al., 2013). Gypsum can also be added with irrigation water to increase the Ca/Na ratio of the water and improve reclamation.

In addition, gypsum amendments significantly decreased exchangeable Na% by increasing the proportion of Ca^{2+} and Mg^{2+} to Na^{+} in soil exchange complex. Therefore, saline soil reclamation involves the conversion of Na-clay into Ca-clay as well as leaching of excess Na.

The addition of organic matter to saline soils increased the CEC, thereby, more nutrients became available to plants. The interaction of soil amendments with the saline paddy ecosystems significantly improved the soil physicochemical properties, which ultimately decreased total seasonal CH_4 emissions and increased rice grain yield. It has been reported that gypsum amendments effectively reduced CH_4 emission from rice paddy under saline and non-saline conditions (Theint et al., 2016). At 25 mM salinity level, CH_4 emissions were decreased by 23%, 27% and 61% with gypsum applications at 1 Mg/ha, 2.5 Mg/ha and 5.0 Mg/ha respectively. The maximum decrease in cumulative CH_4 emissions was recorded 32.6% with Azolla-cyanobacteria plus phospho-gypsum amendments in paddy soils of Bangladesh (Ali et al., 2015). Furthermore, it has been reported that 55% - 72% total seasonal CH_4 emission was reduced from wetland rice fields amended with gypsum (6.6 t/ha) in Philippines. Khatun et al. (2021) reported that CH_4 emissions were suppressed with phospho-gypsum and biochar amendments (5 t/ha) within the salinity level 25 mM to 50 mM. During dry season boro rice cultivation, maximum cumulative CH_4 emission 180 kg/ha and GWPs 4500 kg CO_2 eq. ha^{-1} were recorded from the recommended NPKS (T2), which decreased significantly ($P < 0.01$) with phosphogypsum (PG) and tea waste compost amendments with proline application. On the other hand, during the wet aman season cumulative CH_4 emission 169 kg/ha and GWPs 4225 kg CO_2 eq. ha^{-1} were recorded from NPK fertilized rice field (T2), which were decreased significantly ($P < 0.01$) with phosphogypsum (PG) and tea waste compost amendments with proline application. From this study, the maximum net seasonal return Tk. 41,500/ha and highest benefit to cost ratio (BCR) 1.47 were found in Azolla compost amendments with NPKS fertilizers (T5). In the wet aman season, maximum net seasonal return Tk. 32,000/ha and highest benefit to cost ratio (BCR) index 1.34 were found in Azolla compost amendments with NPKS fertilizers (T5). The lower net seasonal return and BCR ratio were found in the wet aman season compared to dry boro season, which may be due to lower yield potentials of aman rice cultivar. Ali et al., (2014) reported that integrated organic, inorganic and biological amendments increased rice productivity and improved soil quality parameters, while decreased seasonal cumulative CH4 flux under irrigated paddy ecosystem.

After harvesting rice, the overall soil properties such as soil redox status, organic matter content, electrical conductivity, available P, available S, exchangeable K^+ and Ca^{2+}, K^+/Na^+, Ca^{2+}/Na^+ ratios etc. were increased with phospho-gypsum amendment and BGA spirulina inoculation in rice planted field plots. Khatun et al. (2021) reported the highest ratios of K^+/Na^+ and Ca^+/Na^+ were found in the extract of saline soil (at 25 mM) with phospho-gypsum amendments and Spirulina inoculation. Furthermore, soil SO_4^{2-}, NO_3^-, Mn^{4+} and Fe^{3+} contents in rice root rhizosphere were increased in the amended saline soils, which caused significant reduction in seasonal methane emissions. Soil amendments with PG and BGA Spirulina inoculation decreased soil pH and EC value, probably due to the acidifying effect of organic acids produced from the decomposition of organic materials and Phosphogypsum, eventually improved tolerance to salinity and enhanced rice yield and overall productivity. In this study, total N, P, K uptakes of rice plant were significantly increased in Azolla compost applied and PG amendments with cyanobacteria, proline and chemical fertilization treatments in T9, T10 and T5 rice field plots, probably due to higher photosynthesis and yield performance compared to other treatments.

The ratio of $Na^{+/}K^+$ increased in the roots and shoots of rice seedlings (BRRI Dhan 47) under salt-stressed (200 mM NaCl) condition, while decreased with Ca supplementation. Khatun et al., (2021) reported that combined application of phospho-gypsum and biochar with the recommended NPKSZn fertilizers in saline soils may enhance tolerance to salinity in rice by increasing K^+/Na^+, Ca^{2+}/Na^+ ratios, while decreasing yield scaled CH_4 emission (GHGI) within the salinity levels 25 mM to 75 mM. Khan et al. (2019) reported that soil salinity level was decreased by gypsum, calcium chloride, rice husk and cowdung amendments.

5. Conclusion

From the experimental findings, it may be conferred that 25% replacement of chemical fertilizer (NPKS) from the recommended level with soil amendments showed the satisfactory yield performance of rice (4500 - 4900 kg/ha) although seasonal cumulative CH_4 emission, GWPs and GHGI were found minimum in PG and Tea waste amendments along with proline application (T10 and T8 treatments). The 25% replacement of chemical fertilizer (NPKS) with trichocompost (T3), tea waste compost (T4), Azolla compost (T5) and Phospho-gypsum cyanobacteria (T6) increased grain yield by 4.7%, 2.3%, 11.9% and 9.5% compared to chemically fertilized plot (4200 kg/ha). Furthermore, the application of proline with soil amendments increased grain yield by 7.1%, 7.1%, 16.6% and 14.2% in Trichocompost amendment with proline (T7), Tea waste compost with proline (T8), Azolla compost with proline (T9) and PG amendments with cyanobacteria and proline application (T10), respectively, over the chemically fertilized (100% NPKS) plot. The maximum seasonal cumulative CH_4 flux was recorded (185 kg CH_4/ha) in 100% NPKS fertilized plot without any amendments, whereas the lowest CH_4 flux (143 kg/ha), GWPs 3550 and GHGI 0.029 were recorded under PG amendments with 75% NPKS and proline application (T10). Conclusively, soil amendments with Azolla compost, phosphogypsum (PG) with cyanobacteria and tea waste compost along with reduced chemical fertilizers and proline application could be an effective strategy to improve soil salinity stress and sustain rice productivity, while minimizing GWPs from salt affected coastal paddy ecosystem.

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Conflicts of Interest

There is no conflict of interest for this research publication.

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