Soil amendments in suppressing salinity effects on HYV rice cultivars

Md Zamil Uddin[1], Mohammad Ashiqur Rahman[2], Mohammad Abdul Mojid[3*]

(1. Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur, 1706, Bangladesh;
2. Bangladesh Institute of Nuclear Agriculture, Mymensingh, 2202, Bangladesh;
3. Bangladesh Agricultural University, Mymensingh, 2202, Bangladesh)

Abstract: Suppressing the harmful effects of salinity is a critical issue for expanding rice acreage in saline areas under demographic pressure and climate change contexts. In need of comprehensive information, this study evaluated the effectiveness of cowdung and gypsum ($CaSO_4.2H_2O$) for their individual and combined usages in ameliorating salinity stress for cultivation of Binadhan-8 (V_1), Binadhan-10 (V_2), and BRRI dhan47 (V_3) rice cultivars with standard fertilizer doses under irrigation with four salinity levels: fresh water (SL_1, control), 6 dS m^{-1} (SL_2), 9 dS m^{-1} (SL_3), and 12 dS m^{-1} (SL_4). A pot experiment was laid in a Split-Split arrangement in a completely randomized design (CRD) with three factors (soil amendments, salinity levels, and rice cultivars) and three replications. The amendment treatments included: no amendment (T_1, control), cowdung @ 6 t ha^{-1} (T_2), gypsum @ 150 kg ha^{-1} (T_3), and combination of cowdung @ 6 t ha^{-1} and gypsum @ 150 kg ha^{-1} (T_4). SL_4 significantly ($p \le 0.05$) suppressed all attributes of the rice cultivars. Treatments T_3 and T_4 most effectively reduced salinity stress on the rice cultivars, which could tolerate up to 12 d S m $^{-1}$ irrigation-water salinity without significant yield loss, with T_3 performed the best. The generated information would help rice cultivation under irrigation with saline water, specifically in the coastal region having limited fresh water for irrigation.

Keywords: rice, irrigation, salinity stress, amelioration

Citation: Uddin, M. Z., M. A. Rahman, and M. A. Mojid. 2023. Soil amendments in suppressing salinity effects on HYV rice cultivars. Agricultural Engineering International: CIGR Journal, 25(4): 14-33.

1 Introduction

Soil salinization is continuously increasing in many regions of the globe, specifically in the coastal regions, due to sea level rise and sea water intrusion and irrigation with saline water, coupled with an inadequate drainage system. Globally, 833 Mha of soils are salt-affected (FAO, 2021). With the decreasing availability of good quality water in the salinity-affected regions, farmers are being compelled to utilize moderately saline water for irrigation (McFarlane et al., 2016; Gandahi et al., 2017). The scarcity of fresh water in coastal saline areas in the South Asia has led the agricultural scientists to recommend conjunctive use of fresh water and moderately saline water to irrigate crops (Al Khamisi et al., 2013; Mojid and Hossain, 2013; Singh, 2014a; Rahman et al., 2020). The high Na^+ concentrations in soil water or at the cation exchange sites (soil particle surface) make the soil saline sodic with inherent low quality (Yu et al., 2010). Soil structure, soil organic carbon, humus and nutrient contents are the most growth-constraining factors in saline soils (Bello et al., 2021; Gonçalo Filho et al., 2019; Nan et al., 2016). Consequently, salinization is a key issue in agronomy, hydrology, irrigation and soil science

---

Received date: 2022-04-29 **Accepted date:** 2023-07-11

***Correspondence author: Mohammad Abdul Mojid,** Department of Irrigation and Water Management, Bangladesh Agricultural University, Mymensingh, Bangladesh. E-mail: ma_mojid@bau.edu.bd.

(Singh, 2014b; Kivi and Bailey, 2017) and a major environmental threat for agricultural production since it adversely influences ionic, osmotic and nutritional relations of plants.

Several future challenges of food production caused by climate change, such as a rising sea-water level and cyclones, are expected to increase salt-water intrusion and augment soil salinity in Bangladesh. The coastal region of the country is affected both by soil and water salinity (Hoque and Haque, 2016; Parvin et al., 2017; Rahman et al., 2017). Approximately 3.56 Mha of arable lands, including coastal and inland areas, are already affected by soil salinity (SRDI, 2016). But, management of soil salinity to increase crop and land productivity has not yet received adequate attention although demand for food for the growing population is increasing. So, it has become crucial to continuously develop appropriate and effective techniques to manage salt-affected soils for crop production. One feasible option could be irrigating suitable crops with the ample sources of saline water with appropriate soil and water management practices, which are yet to be established.

Permanent reclamation of the saline soils is difficult, costly and complex, and also impossible when frequent inundation and tidal flooding are present. In a comprehensive review, Gupta and Huang (2014) described the major research advances on biochemical, physiological, and molecular mechanisms, which regulate plants' adaptation and tolerance to salinity stress. Agronomic practices that can reduce salinity level of a soil or alleviate the effects of salinity on plants can be feasible approaches (Shaaban et al., 2013). For example, application of organic (e.g., cow dung) and chemical (e.g., gypsum) amendments, and adoption of proper irrigation methods may be effective agronomic management practices for reducing the harmful effects of salinity stress in crop production. Incorporation of organic materials into soil also has other beneficial effects on soil physical, chemical, and biological properties (Iqbal et al., 2016; Chahal et al., 2017; Leogrande and Vitti, 2019). Cultivating salt-tolerant crop varieties (halophytes) is another option to utilize saline soils in agriculture. Yet salinity in most coastal regions is very often too high for such crop varieties.

Therefore, combining salt-tolerant rice varieties with suitable soil amendments and proper water management practice is crucial to combat the unwanted effects of salinity on rice plants. In this regard, rice production management by suppressing salinity stress through soil amendments in the coastal areas of Bangladesh is essential to increase food production for the growing population. This study intended to evaluate three soil amendments to ameliorate salinity effect on three salt-tolerant HYV rice cultivars and to find out the scope of using saline water for irrigation in combination with suitable soil amendment practice(s).

2 Materials and methods

2.1 Experimental site and climate

The experiment was done during December to May of 2015–16 and 2016–17 at the Field Lysimeter Yard of Bangladesh Institute of Nuclear Agriculture (BINA) at Mymensingh, Bangladesh. The site is in the Agro-Ecological Zone (AEZ) 9 (24°75' N latitude and 90°50' E longitude). The monthly maximum temperature during December to May varied from 24.2^o C to 33.5^{o}C in 2015–2016 and 26.7^{o}C to 33.5^{o}C in 2016–2017. The monthly minimum temperature varied from 12.2^{o}C to 23.9^{o}C and 12.9^{o}C to 23.2^{o}C, and the monthly average relative humidity varied from 79.5% to 88.9% and 78.2% to 87.0% during the corresponding period. Total rainfall during the corresponding period was 613 mm and 767 mm.

2.2 Experimental design and layout

The growth and yield performances of Binadhan-8 (V_1), Binadhan-10 (V_2) and BRRI dhan47 (V_3) were investigated under four soil amendments: no amendment as control (T_1), cowdung @ 6 t ha^{-1} (T_2), gypsum ($CaSO_4.2H_2O$) @ 150 kg ha^{-1} (T_3), and combination of cowdung @ 6 t ha^{-1} and gypsum @ 150 kg ha^{-1} (T_4); all treatments were associated with recommended fertilizer dose for rice cultivation. The treatments were combined with four salinity levels of irrigation water: fresh water (SL_1), 6 (SL_2), 9 (SL_3) and 12 (SL_4) dS m^{-1}. The three-factor factorial experiment with soil amendments as main factor, salinity levels as sub-factor and rice varieties as sub-sub-factor was laid out in a Split-Split pot completely randomized design with three replications. The total number of pots (plastic buckets, each of 16 liters capacity) was 144 (4 amendments × 4 salinity levels × 3 rice cultivars × 3 replications). The layout of the experiment is illustrated in Figure 1.

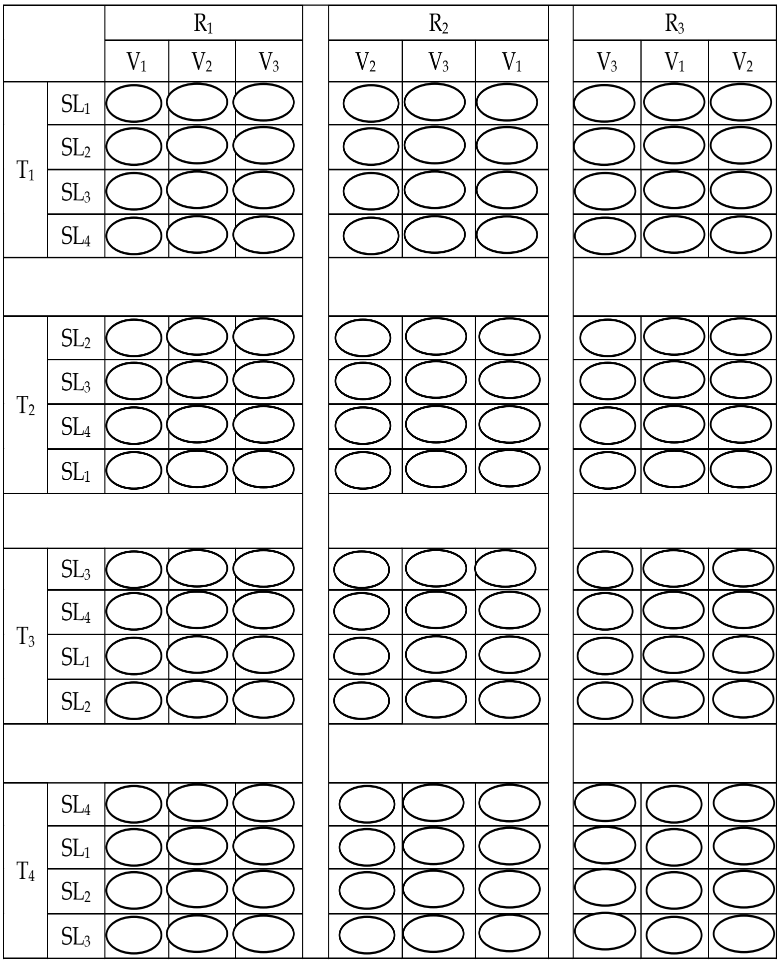


Figure 1 Experimental layout in pots with four soil amendments (T_1–T_4), four salinity levels (SL_1–SL_4) and three rice varieties (V_1–V_3)

2.3 Field experimentation

Well-pulverized and sun-dried soil, collected from 0–15 cm soil profile from BINA farm, was mixed thoroughly after removing the foreign and inert materials and breaking the soil clods to obtain approximately homogeneous soil mass. Three samples (each of 1 kg) were collected from the soil-lot and their (pre-planting) physico-chemical properties were determined following standard laboratory procedures. The loam soil (51.1% sand, 36.7% silt and 12.2% clay) had a volumetric moisture content of 0.39 at field capacity and 0.18 at wilting point. Each experimental pot was filled with 15 kg air dry homogeneous soil. Basal dose fertilizers of triple super phosphate (TSP), muriate of potash (MP) and zinc sulphate @ 1.7, 1.2 and 0.1 g per pot, respectively corresponding to the recommended dose of 100, 70 and 3.61 kg ha^{-1} were mixed with the soils in the pots. Cowdung manure (CoM) @ 100 g per pot (@ 6 t ha^{-1}) was mixed with soil in the pots as per treatment. The main properties of CoM are provided in Table 1.

Seedlings of the rice varieties were grown in nursery beds by sowing the rice seeds on 18 December 2015 and 26 December 2016. The soils in the pots were puddled by adding 5 liters tap water, which was sourced from a nearby deep tubewell and the seedlings were transplanted in the pots on 28 January 2016 and 26 January 2017. Each pot accommodated one hill of one plant. Urea @ 1.5 g per pot (@ 271.74 kg ha^{-1}) was top dressed at 11, 32 and 60 days after transplanting (DAT), and gypsum @ 1.5 g per pot (@ 150 kg ha^{-1}) was applied at 15 and 60 DAT. Weeding and plant protection measures were done as and when these were necessary. The experimental pots were protected from rainfall during the entire growing season by placing them under a shed of transparent plastic sheet set over a pre-constructed cast iron frame. The transparent shed did not prevent sunlight significantly from reaching the rice plants but helped maintaining proper control on water budget and salinity levels of the applied irrigation water.

Table 1 Properties of cowdung manure (CoM)

Quality parameters	Parameter values
pH	7.65
EC (dS m–1)	3.17
Organic carbon (g kg–1)	257
Organic matter (%)	44.46
Total-N (g kg–1)	15
C/N ratio	17.13
Moisture content (%)	58
Dry matter (%)	42
Total P (g kg–1)	8.9
Sulphur (g kg–1)	3.1
Exchangeable Potassium (g kg–1)	5.45
Exchangeable Sodium (Na) (g kg–1)	3.84
Exchangeable Calcium (Ca) (g kg–1)	4.06
Exchangeable Magnesium (g kg–1)	3.22

2.4 Irrigation practices

Groundwater of a deep tubewell within BINA farm was used as fresh water, SL_1, for irrigation. Raw wet salt was collected from a salt field in the coastal saline area of Chattogram district and irrigation water for SL_2, SL_3 and SL_4 salinity levels was prepared with this salt. So, the ingredients of saline irrigation water were same as of sea water. Total 4.8, 7.2 and 9.6 g raw salt when mixed separately in one-liter fresh water provided 6, 9 and 12 dS m^{-1} salinity, respectively at 25°C. Irrigation water for SL_1 falls under non-saline class and that for SL_2, SL_3 and SL_4 fall under different high salinity classes based on classification of US Salinity Laboratory Staff (1954). All other quality parameters (Table 2) of irrigation water with salinity levels SL_2, SL_3 and SL_4 were within the recommended quality criteria for safe usage in agriculture. The required quantity of irrigation water for each salinity level was prepared during each irrigation event by mixing salt with fresh water. Fresh water was applied to the pots selected for SL_1 treatment (Figure 1); the other pots were irrigated with water of required salinity levels. A 3–5 cm ponding water depth was maintained to ensure normal growth of rice plants by applying 1–3 liters water. Total 14 irrigations were applied during 2015–16 and 21 irrigations during 2016–17 crop seasons.

2.5 Data measurement and analysis

The rice cultivars were harvested pot-wise at full maturity on 2, 8 and 9 May for the 2015–16 experiment and on 18 and 20 May for 2016–17 experiment; the maturity date varied for different rice cultivars. The harvested crop was bundled and tagged separately for each pot and sun dried properly. Plant height and panicle length were measured with a measuring tape. Total and effective tillers per hill were counted. Rice grains of each hill were separated and weighed after sun drying at 12% moisture content. One thousand sun-dried grains were taken from the grain stock of each pot and weighed. The straw of each pot was weighed after sun drying. Since standard plant spacing could not be maintained in the pots, we expressed the grain and straw yields ‘per hill basis’ instead of per area (hectare) basis. This did not hamper comparing relative performance of the factors and treatments of the experiment. Harvest index (HI) of rice was calculated from the ratio of grain yield to the total above-ground biomass yield (grain and straw yields). For recording data on roots, the rice hill for each pot was uprooted with a soil column of 10 cm diameter and 30 cm depth since most of the root system remained within this soil volume. The roots with the soil were kept on plastic nets and washed carefully with water to remove the soil and separate the roots. Length of the roots was measured and after oven-drying at 60°C for 72 h their weight was measured for each pot. Soil samples were collected at harvest from each pot and analyzed following standard laboratory procedures for bulk density, porosity, texture, unsaturated hydraulic conductivity, pH, electrical conductivity (EC), organic matter, total nitrogen, available phosphorus, available sulphur, exchangeable cations (K^+, Ca^{++}, Na^+, Mg^{++}) and sodium adsorption ratio (SAR).

The analysis of variance (ANOVA) was done for the data on plant attributes and soil properties by using Statistix 10 software package of Analytical Software (2019) to identify significance of the treatments in the variation of the plant attributes and soil properties. Comparisons of means of the plant attributes among the amendment treatments, salinity levels and rice cultivars, and soil properties among the amendment treatments and salinity levels were done using Tukey's HSD test at 5% level of significance ($p \leq 0.05$).

Table 2 Quality parameters of irrigation water of four salinity levels (SL_1, SL_2, SL_3 and SL_4) along with the FAO/WHO standard

Quality parameters	Salinity level				FAO/WHO standard
	SL_1	SL_2	SL_3	SL_4	
EC (dS m^{-1})	0.37	6.00	9.00	12.00	0–3
Total-Nitrogen (%)	4.06	4.90	4.06	4.62	0–10
Available Phosphorus (mg L^{-1})	0.12	0.11	0.12	0.13	0–2
Available Sulphur (mg L^{-1})	2.99	45.54	79.88	129.14	-
Exchangeable Potassium (meq L^{-1})	0.04	0.29	0.43	0.54	0–2
Exchangeable Sodium (Na) (meq L^{-1})	0.84	5.55	8.80	12.13	0–40
Exchangeable Calcium (Ca) (meq L^{-1})	1.06	4.82	6.63	8.80	0–20
Exchangeable Magnesium (meq L^{-1})	4.22	4.35	4.48	4.53	0–5
SAR (-)	0.52	2.59	3.74	4.70	0–15
pH (-)	7.08	7.65	7.92	8.32	6.5–8.4

Note: SL_1: fresh water, SL_2: 6 dS m^{-1}, SL_3: 9 dS m^{-1} and SL_4: 12 dS m^{-1}

3 Results

3.1 Post-harvest soil quality

SAR, and EC of the post-harvest soils increased significantly ($p \leq 0.05$) due to salinity of the applied irrigation water, with their highest values of 1.607 and 3.33 dS m^{-1}, respectively under SL_4 and the lowest values of 0.322 and 0.341 dS m^{-1}, respectively under SL_1. EC of the saturated-soil extract, available phosphorus and sulphur, exchangeable cations (calcium, sodium and magnesium), SAR, and pH increased, while organic matter and total nitrogen contents decreased with increasing salinity of irrigation water (Table 3). Soil amendments (treatments T_2, T_3 and T_4) suppressed the salinity effects and reduced SAR and EC significantly compared to non-amended soils (T_1). The degree of suppressing effect differed significantly among different amendments. These results imply that soil amendments can reclaim saline soils, and combined use of gypsum and cowdung as amendment is superior in the recovery compared to their alone use. These results are in agreement with findings of Ullah and Bhatti (2007) and Mahmoodabadi et al. (2013).

3.2 Plant height

Salinity stress suppressed plant height of the rice cultivars; the suppressive effect increased significantly ($p \leq 0.05$) with the increase in salinity level (Table 4). Plant height also varied among the rice cultivars; Binadhan-10 (V_2) produced significantly taller plants than the other cultivars, and BRRI dhan47 (V_3) produced significantly taller plants than Binadhan-8 (V_1) (Table 5). Soil amendments suppressed salinity effects and helped producing taller plants compared to the control (T_1) (Table 6). The mean plant height varied significantly among the amendments under the combined effects of four salinity levels of irrigation water and three salt-tolerant HYV Boro rice cultivars, with the tallest plant in treatment T_3 and the shortest plant in T_1. Plant height varied significantly among the amendment treatments for different salinity levels irrespective of the rice cultivars. Soil amendments suppressed salinity stress on plant height; the degree of suppression depended on the type of amendment and salinity levels of irrigation water. T_3 and T_4

amendments produced significantly taller plants under high salinity levels (SL_3 and SL_4) than other treatments (Figure 2a), thus revealing them as the best soil amendments under irrigation with saline water. Plant height increased for all rice cultivars under the amendments (T_2–T_4) compared to the control/no amendmemnt irrespective of the salinity levels (Figure 2b).

Table 3 Chemical properties of pre-planting soil and post-harvest soils as affected by soil amendments (T_1, T_2, T_3 and T_4) and irrigation water salinity (SL_1, SL_2, SL_3 and SL_4)

Amend-ment / Salinity levels	Organic mater (%)	Total-nitrogen (%)	Available phosphorus (mg kg^{-1})	Available sulphur (mg kg^{-1})	Exchangeable potassium (meq 100 g^{-1} soil)	Exchangeable sodium (meq 100 g^{-1} soil)	Exchangeable calcium (meq 100 g^{-1} soil)	Exchangeable magnesium (meq 100 g^{-1} soil)	SAR (-)	EC (dS m^{-1})	pH (-)
Pre-planting soil properties											
1.26	0.073	9.65	15.42	0.084	0.511	3.612	3.62	0.269	0.375	6.75	1.26
Post-harvest soil properties											
T_1	1.25b	0.11a	13.037b	24.974c	0.659a	1.909a	2.035bc	3.478b	1.142a	2.156a	7.98a
T_2	1.32a	0.10ab	15.902a	23.505c	0.103b	1.780b	2.104ab	3.519ab	1.055b	2.023b	7.95a
T_3	1.25b	0.09b	13.481b	42.676a	0.09b	1.585c	2.159a	3.514ab	0.936c	1.73c	7.63c
T_4	1.35a	0.10ab	16.078a	38.925b	0.09b	1.467d	1.967c	3.553a	0.876d	1.689c	7.80b
$HSD_{0.05}$	0.0623	0.0099	1.603	2.1213	0.0571	0.0699	0.1071	0.0498	0.032	0.117	0.059
SL_1	1.36a	0.11a	12.853b	29.688c	0.286a	0.526d	1.878c	3.437c	0.322d	0.341d	7.55d
SL_2	1.28b	0.1ab	15.012a	31.906b	0.091b	1.52c	2.075b	3.505b	0.910c	1.578c	7.76c
SL_3	1.28b	0.1bc	15.187a	34.069a	0.272a	1.966b	2.126ab	3.533b	1.169b	2.349b	7.9b
SL_4	1.24b	0.09c	15.447a	34.417a	0.293a	2.729a	2.186a	3.591a	1.607a	3.33a	8.16a
$HSD_{0.05}$	0.0497	0.0111	1.0756	1.7108	0.023	0.0465	0.083	0.0317	0.0281	0.103	0.062

Note:Common letter(s) within the same column do not differ significantly at 5% level of significance ($p \leq 0.05$)

Table 4 Growth and yield attributes, yield, harvest index, and water productivity of rice as influenced by salinity (SL_1, SL_2, SL_3 and SL_4) under combined effects of soil amendments and rice cultivars

Irrigation water salinity level	Plant height (cm)	Total tillers per hill (no)	Effective tillers per hill (no)	Panicle length (cm)	Total grains (no)	Filled grains (no)	Unfilled grains (%)	Thousand grain weight (g)	Grain yield per hill (g)	Straw yield per hill (g)	Harvest index (%)	Root-biomass yield (g)	Water productivity (kg ha^{-1} cm^{-1})
SL_1	99.7a	30.8a	26.1a	26.5a	172.1a	132.4a	23.1d	93.1a	93.1a	34.5a	72.9a	41.9a	152.5a
SL_2	97.5b	25.1b	20.8b	25.8b	164.1b	123.3b	25.0c	70.1b	70.1b	30.0b	69.8b	37.7b	121.8b
SL_3	95.1c	23.4c	18.4c	24.9c	150.5c	111.0c	26.4b	56.1c	56.1c	24.3c	69.3b	33.3c	105.8c
SL_4	92.7d	20.4d	15.4d	23.8d	130.7d	92.9d	29.3a	40.3d	40.3d	21.1d	64.8c	25.8d	83.0d
$HSD_{0.05}$	0.746	0.974	0.786	0.389	4.338	2.299	1.438	2.077	2.077	0.876	0.732	0.981	3.85

Note:Common letter(s) within the same column do not differ significantly at 5% level of significance ($p \leq 0.05$)

Table 5 Growth and yield attributes, yield, harvest index, and water productivity of rice cultivars (V_1, V_2 and V_3) under combined effects of soil amendments and irrigation water salinity

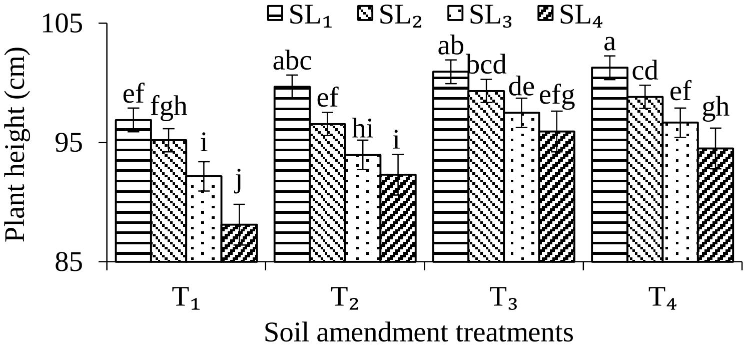
Cultivars	Plant height	Total tillers per hill	Effective tillers per hill	Panicle length	Total grains	Filled grains	Unfilled grains	Thousand grain weight	Grain yield per hill	Straw yield per hill	Harvest index	Root-biomass yield	Water productivity
	(cm)	(no)	(no)	(cm)	(no)	(no)	(%)	(g)	(g)	(g)	(%)	(g)	(kg ha^{-1} cm^{-1})
V_1	90.9c	24.4b	19.8b	25.1b	155.2b	115.2b	26.1b	63.7b	63.7b	26.5b	69.5a	30.1c	113.7b
V_2	106.4a	26.3a	21.3a	25.9a	162.2a	123.6a	24.0c	72.8a	72.8a	30.4a	69.9a	40.5a	130.1a
V_3	91.4b	24.1b	19.4b	24.7c	145.7c	105.9c	27.7a	58.2c	58.2c	25.5c	68.2b	33.4b	103.5c
$HSD_{0.05}$	0.448	0.549	0.586	0.273	2.958	2.217	1.230	1.647	1.647	0.635	0.649	0.715	2.906

Note:Common letter(s) within the same column do not differ significantly at 5% level of significance ($p \leq 0.05$)

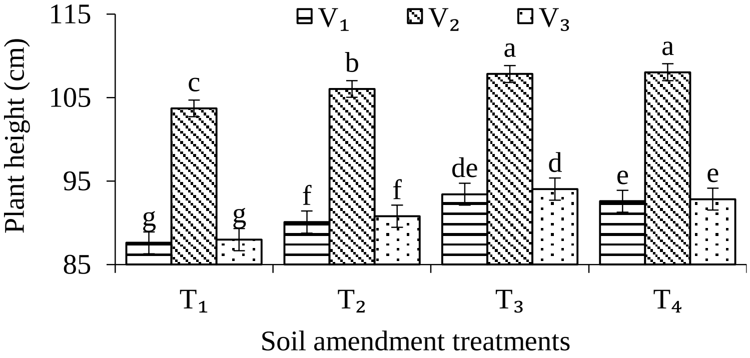
Table 6 Growth and yield attributes, yield, harvest index, and water productivity of rice for soil amendments (T_1, T_2, T_3 and T_4) under combined effects of irrigation water salinity and rice cultivars

Amendment treatments	Plant height (cm)	Total tillers per hill (no)	Effective tillers per hill (no)	Panicle length (cm)	Total grains (no)	Fill grains (no)	Unfilled grains (%)	Thousand grain weight (g)	Grain yield per hill (g)	Straw yield per hill (g)	Harvest index (%)	Root-biomass yield (g)	Water productivity (kg ha^{-1} cm^{-1})
T_1	93.1d	23.0c	18.6b	24.2c	140.3c	99.8c	29.3a	26.9d	52.3d	22.9d	67.5c	30.1d	94.1d
T_2	95.6c	24.3b	19.3b	25.1b	150.6b	110.0b	27.2b	27.4c	58.8c	26.3c	68.3b	31.9c	105.6c
T_3	98.4a	25.8a	21.4a	25.9a	161.7a	124.4a	23.2d	27.8b	72.5b	29.5b	70.6a	37.3b	128.9b
T_4	97.8b	26.5a	21.3a	25.9a	164.8a	125.4a	24.0c	28.01a	76.0a	31.1a	70.4a	39.3a	134.6a
HSD $_{0.05}$	0.408	0.974	0.934	0.476	3.261	1.856	0.798	0.167	0.193	0.433	0.767	1.023	3.454

Note:Common letter(s) within the same column do not differ significantly at 5% level of significance ($p \le 0.05$)



(a) Four salinity levels under four amendments irrespective of three rice cultivars

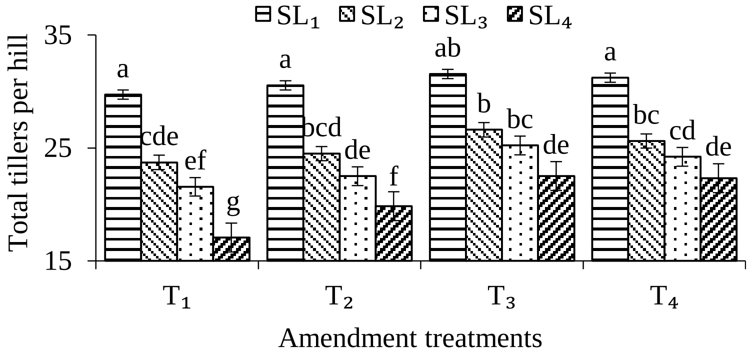


(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

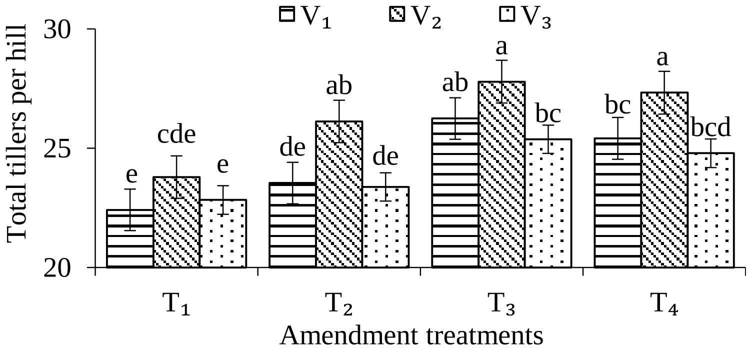
Figure 2 Comparison of plant height of rice

3.3 Total and effective tillers per hill

Compared to fresh-water (SL_1), saline-water suppressed the number of total and effective tillers; the suppressing effect increased significantly with increasing salinity level (Table 4). The total tillers per hill also varied significantly among the three rice cultivars (Table 5), with V_2 producing significantly larger number of total and effective tillers per hill than the other cultivars, which produced similar number of these tillers (Table 5). Soil amendments augmented the total and effective tillers per hill under the combined influence of salinity and rice cultivars (Table 6). Treatments T_3 and T_4 provided similar but significantly larger number of total and effective tillers compared to the other treatments. Significantly higher number of total and effective tillers per hill under T_3 and T_4 revealed these treatments as the best amendment practices under saline-water irrigation. These observations are similar to that reported by Oo et al. (2010). Amendments T_3 and T_4 provided significantly higher number of total tillers under SL_4 than the other treatments irrespective of the rice cultivars (Figure 3a). The amendments significantly improved number of total tillers for all rice cultivars (Figure 3b). Saline water (SL_2–SL_4) without soil amendment (T_1) imposed a strong salinity stress and significantly reduced the effective tillers in most cases (Figure 4a). The mean effective tillers per hill showed significant differences among the rice cultivars under the combined effects of amendments and salinity levels (Figure 4b). Cultivar V_2 produced significantly larger number of effective tillers compared to the other cultivars. The variation of tiller number among the rice varieties was also observed by Dutta et al. (2014).

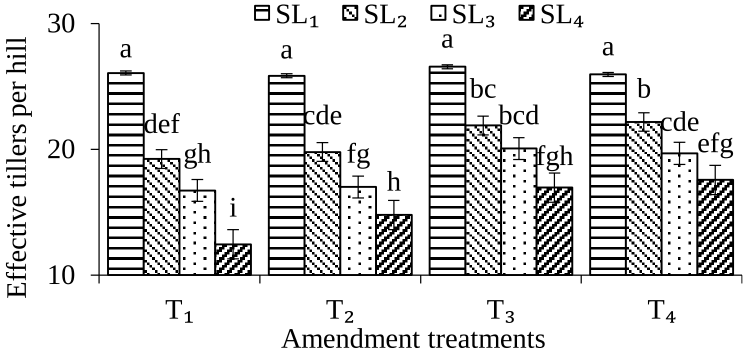


(a) Four salinity levels under four amendments irrespective of three rice cultivars

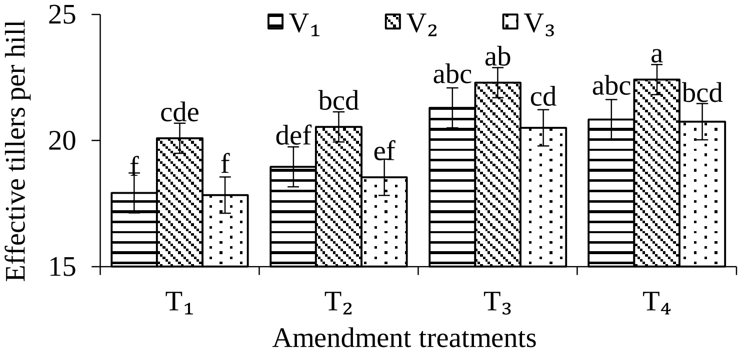


(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

Figure 3 Comparison of total tillers per hill of rice



(a) Four salinity levels under four amendments irrespective of three rice cultivars



(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

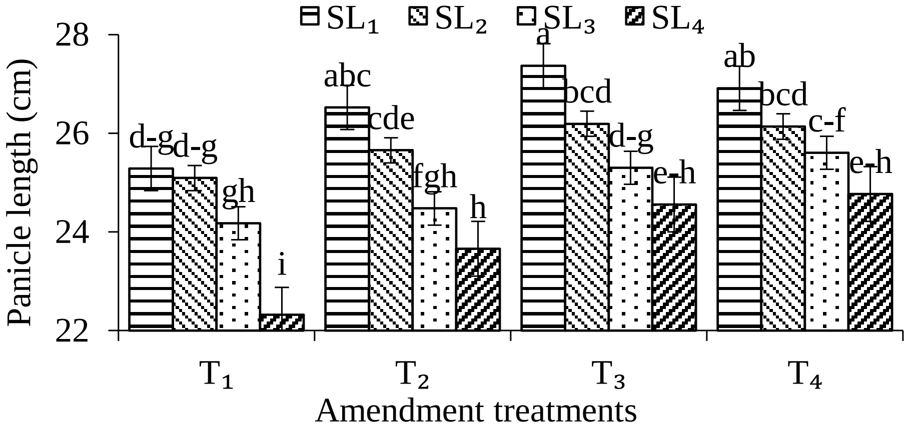
Figure 4 Comparison of effective tillers per hill of rice

3.4 Panicle length

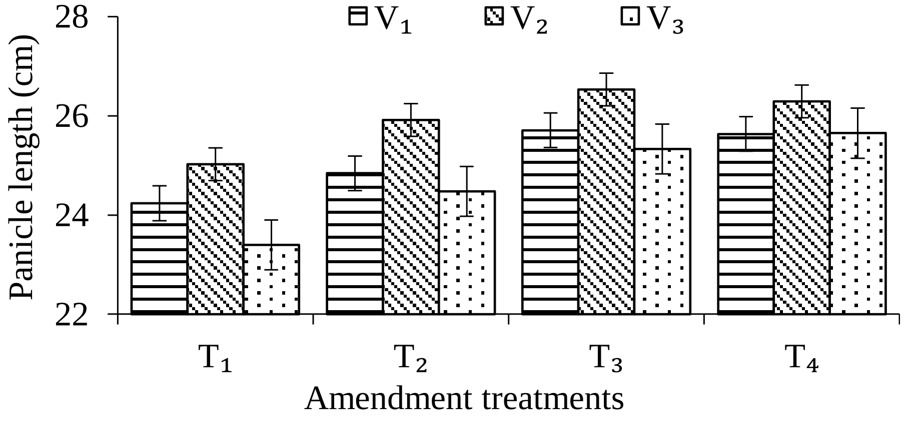
The panicle length of the rice cultivars decreased significantly as salinity increased (Table 4) as was also reported by Karim (2007), Rana (2007) and Rad et al. (2012). The mean panicle length under the combined effects of the amendments and salinity levels differed significantly among the three rice cultivars; cultivar V_2 produced the longest panicles (Table 5). Soil amendments significantly improved the panicle length of rice under the combined effects of salinity and rice cultivars, with the longest panicle produced under T_3 and T_4 (Table 6). Treatments T_3 and T_4 produced significantly longer panicles than other amendments under saline-water irrigation (Figures 5).

3.5 Total and filled grains per panicle

The number of total and filled grains decreased significantly with the increase in salinity (Table 4). The mean grains under the combined effects of the amendments and salinity levels differed significantly among the rice cultivars; V_2 produced the largest number and V_3 the lowest number of grains per panicle (Table 5). Compared to fresh water, saline water suppressed grain production in the panicles; the suppressing effect increased with the increasing salinity level. Soil amendments significantly increased the number of total and filled grains per panicle under the combined effects of salinity and rice cultivars. Treatments T_3 and T_4 produced similar but significantly larger number of total and filled grains than the other treatments (Table 6). Irrigation with saline water with no amendment, T_1, imposed strong salinity stress and reduced the grains. But amendments T_3 and T_4 minimized salinity stress and significantly improved the grains (Figure 6). Treatments T_2–T_4, irrespective of the salinity levels, significantly improved the number of grains of the three rice cultivars compared to T_1 (Figure 7) thus revealing their effectiveness.

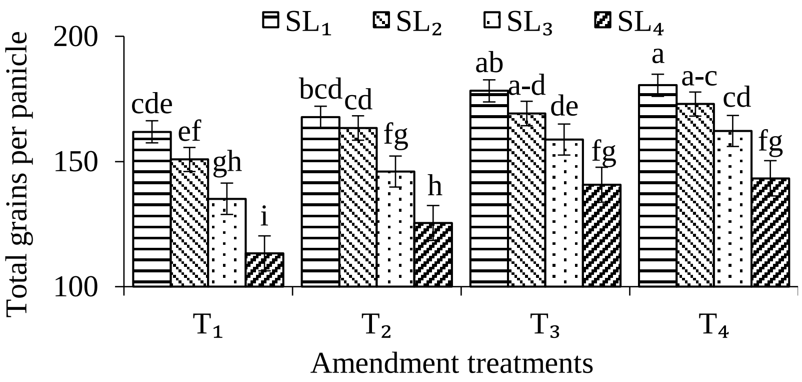


(a) Four salinity levels under four amendments irrespective of three rice cultivars

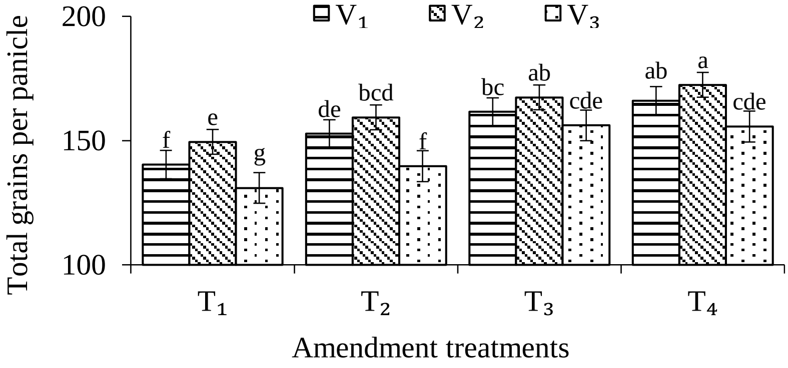


(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

Figure 5 Comparison of panicle length of rice

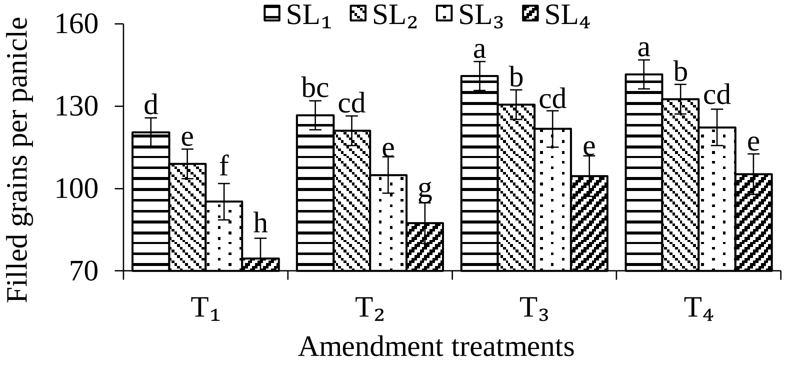


(a) Four salinity levels under four amendments irrespective of three rice cultivars

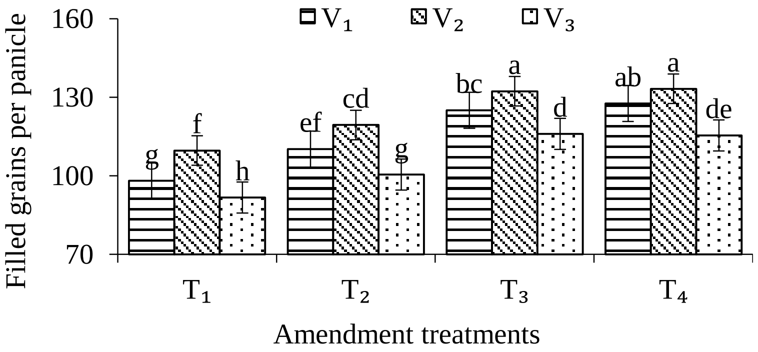


(a) Four salinity levels under four amendments irrespective of three rice cultivars

Figure 6 Comparison of total grains per panicle of rice



(a) Four salinity levels under four amendments irrespective of three rice cultivars

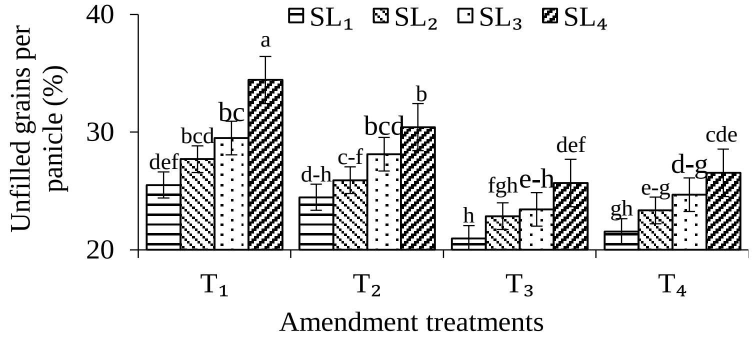


(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

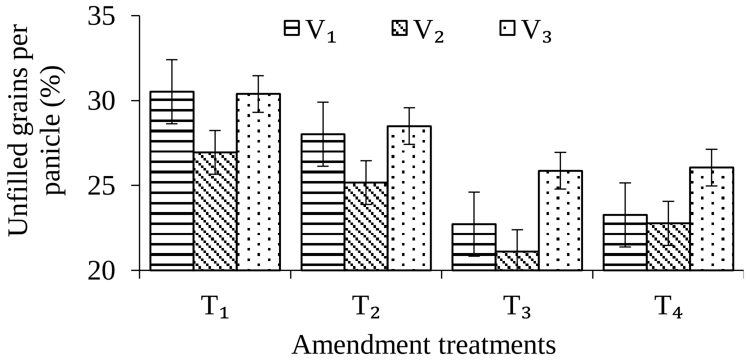
Figure 7 Comparison of filled grains of rice

3.6 Unfilled grains per panicle

The unfilled grains increased significantly with the increase in salinity (Table 4) and varied significantly among the rice cultivars under the combined impacts of the amendments and salinity levels; V_2 produced the lowest and V_3 the highest percentage of unfilled grains (Table 5). Soil amendments significantly reduced unfilled grains of the rice cultivars. The mean unfilled grains varied significantly among the amendments under the combined impacts of salinity levels and rice cultivars; amendment T_3 produced the lowest percentage (23.2%) of unfilled grains (Table 6). Amendments T_3 and T_4 produced significantly lower percentage of unfiled grains under high salinity for the three rice cultivars compared to T_1, with V_2 producing the minimum and V_3 the maximum percentage of unfilled grains (Figure 8).



(a) Four salinity levels under four amendments irrespective of three rice cultivars



(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

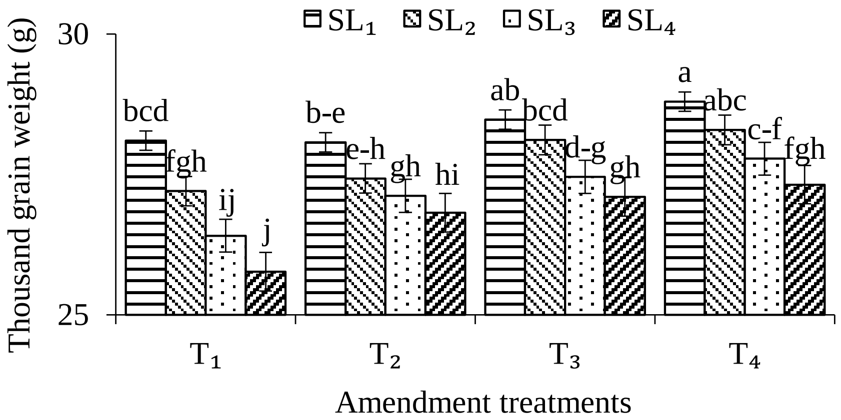
Figure 8 Comparison of unfilled grains of rice

3.7 Weight of 1000 grains

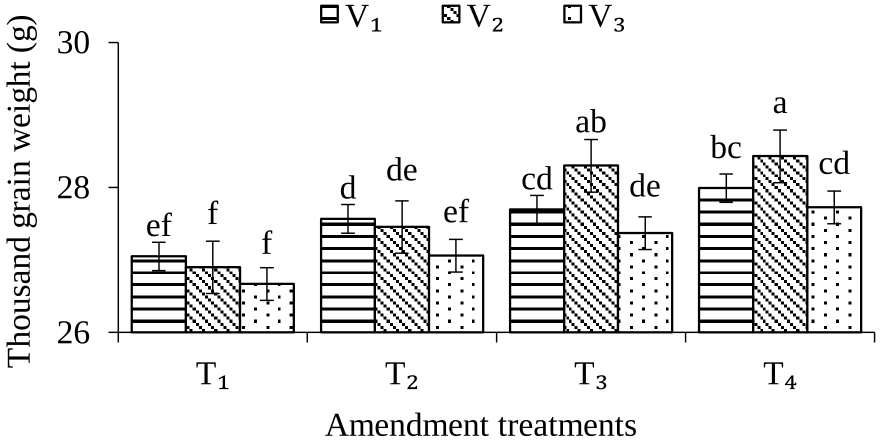
Under the combined impacts of the amendments and rice cultivars, salinity of irrigation water exerted significant detrimental influence on 1000-grain weight (Table 4). Also, the weight of 1000 grains varied significantly among the rice cultivars under the combined effects of the amendments and salinity levels (Table 5), with V_2 producing the highest and V_3 the lowest 1000-grain weights. Soil amendments augmented 1000-grain weight, which varied significantly among the amendments (Table 6). Amendment T_4 produced significantly higher 1000-grain weight under SL_4 than the other amendments irrespective of the rice cultivars (Figure 9), revealing it as the best amendment practice.

3.8 Grain yield per hill

The grain yield decreased significantly with increasing salinity under the combined effects of amendments and rice cultivars (Table 4). Under the combined impacts of amendments and salinity V_2 produced significantly higher grain yield than the other two rice cultivars (Table 5), implying that there are genetic variation of the rice cultivars in their salt tolerance level. Varying degrees of salt tolerance within the varieties of a species were also reported by Pang et al. (2010). Soil amendments significantly improved the grain yield by minimizing the salinity stress under the combined effects of salinity and rice cultivars (Table 6). The maximum grain yield was obtained T_4 amendment followed by T_3 and T_2; both T_3 and T_4 comprised gypsum and T_4 comprised cowdung and gypsum. Increase in rice yield under gypsum application in saline soil was also reported in literature (Khattak et al., 2007). Treatments T_3 and T_4 minimized the harmful effects of salinity and improved grain yield significantly under saline condition than the other treatments. The observed maximum grain yield under T_4 treatment is in agreement with the findings of Oo et al. (2010) and Dutta et al. (2014) who found that using the combination of cowdung and inorganic fertilizers significantly increased yield when compared to the treatments of using cowdung alone. High salinity, SL_4, under T_1 imposed strong salinity stress and resulted in the lowest grain yield (Figure 10). The amendments significantly improved grain yield of the rice cultivars irrespective of salinity levels, with V_2 producing higher grain yield than the other cultivars.



(a) Four salinity levels under four amendments irrespective of three rice cultivars

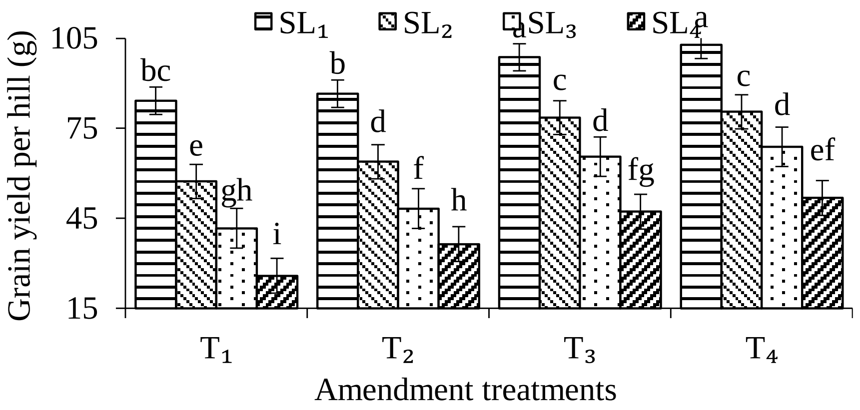


(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

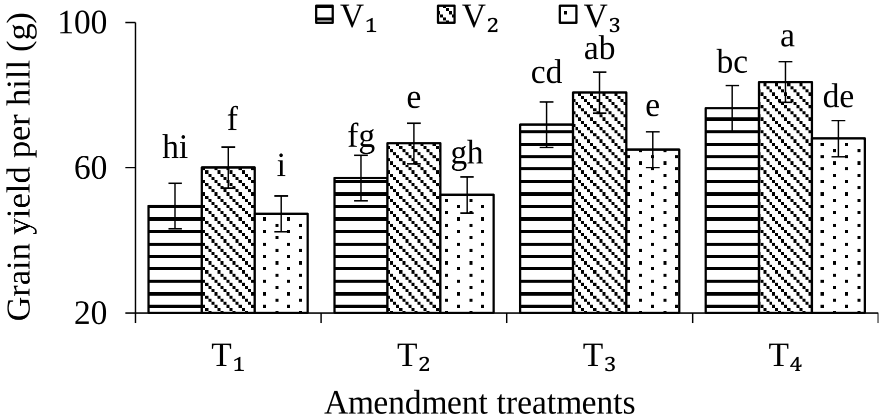
Figure 9 Comparison of thousand grain weight of rice

3.9 Straw yield per hill

Straw yield decreased significantly with increasing salinity level (Table 4) and varied significantly among the rice cultivars under the combined effects of amendments and salinity levels; V_2 produced the highest and V_3 the lowest straw yields (Table 5). Soil amendments exerted significant positive impact on straw yield; the highest straw yields were obtained with T_4 and the lowest were with T_1 (Table 6). Amendment T_4 contributed significantly to augment straw yield under all salinity levels compared to the other treatments (Figure 11). All rice cultivars provided significantly improved straw yield under T_4 compared to the other amendments irrespective of salinity levels. Significantly different straw yield in various rice varieties due to the effect of organic amendments was also observed by Choudhary et al. (2004). With the increasing salinity levels, all the rice attributes significantly degraded, which lowered the yield (Sexcion et al., 2009).



(a) Four salinity levels under four amendments irrespective of three rice cultivars



(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

Figure 10 Comparison of grain yield per hill of rice

3.10 Root-biomass yield per hill

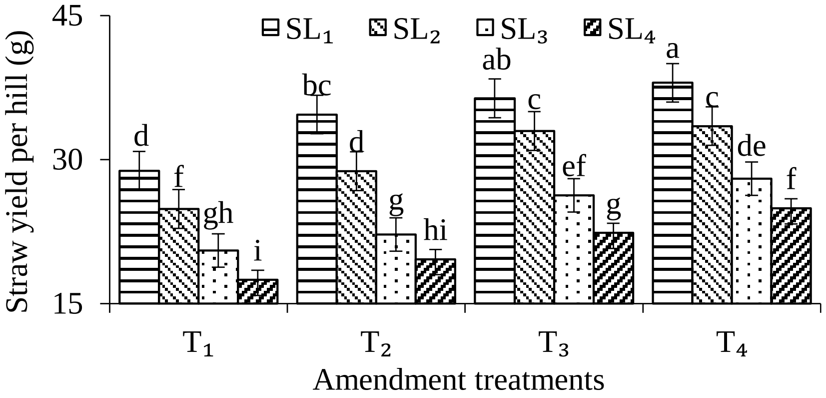
The root-biomass decreased with increasing salinity irrigation water and varied significantly among the rice cultivars (Table 4). Cultivar V_2 produced significantly higher root-biomass under the combined impacts of the amendments and salinity levels compared to the other cultivars (Table 5). The amendments augmented root-biomass, which differed significantly among the amendment treatments under the combined effects of salinity levels and rice cultivars; T_4 produced the highest root-biomass (Table 6). Treatments T_3 and T_4 helped producing significantly higher root-biomass under high salinity than the other treatments (Figure 12). All rice cultivars produced significantly higher root-biomass under T_3 and T_4 than under other treatments irrespective of the salinity levels.

3.11 Harvest index

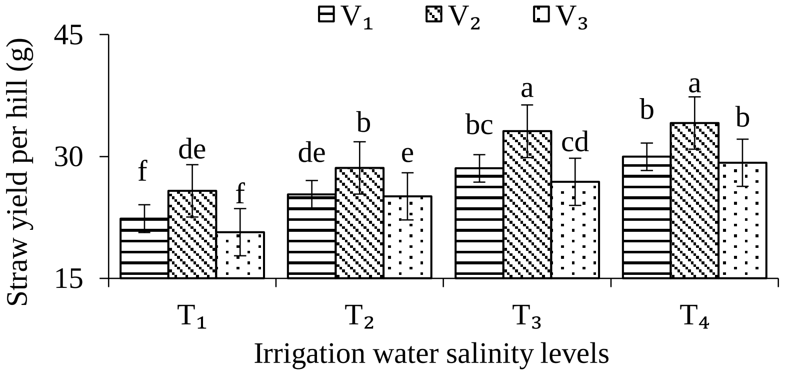
Salinity exerted significant negative impact on harvest index, which decreased as salinity increased (Table 4). Cultivars V_1 and V_2 provided similar but significantly higher HI compared to V_3 (Table 5). Soil amendments exerted significant positive impact on HI irrespective of the salinity levels and rice cultivars (Table 6). Treatments T_3 and T_4 provided similar but higher HI compared to the other treatments. Similar effect of soil amendments on HI of rice was also reported by Aref (2013). It is noted that the observed HI was generally larger compared to that found for rice at field level. The observed higher HI might be due to the growth management under controlled condition in the pots where most of the growth-regulating factors were properly maintained. Treatments T_3 and T_4 provided significantly higher HI under saline conditions (SL_2−SL_4) than the other amendments (Figure 13), thus revealing them as the best soil amendments.

3.12 Water productivity

Water productivity of rice decreased significantly with the increasing salinity for the rice cultivars (Table 4). It varied significantly among the rice cultivars under the combined effects of amendments and salinity, with V_2 providing the largest and V_3 the lowest water productivity (Table 5). The amendments exerted significant impact on the water productivity irrespective of the effects of the salinity levels and rice cultivars (Table 6). The amendments ameliorated salinity effect with resulting increase in yield, which improved the water productivity of rice. Treatment T_4 providing the highest water productivity appeared to be the most effective soil amendment compared to the other treatments. Siam et al. (2015) reported application of organic manure and gypsum as an effective way to ameliorate the salinity stress in rice. Treatment T_4 helped producing significantly higher water productivity under all salinity levels compared to the other amendments (Figure 14). All rice cultivars provided significantly higher water productivity under soil amendments compared to the control/ no amendment.

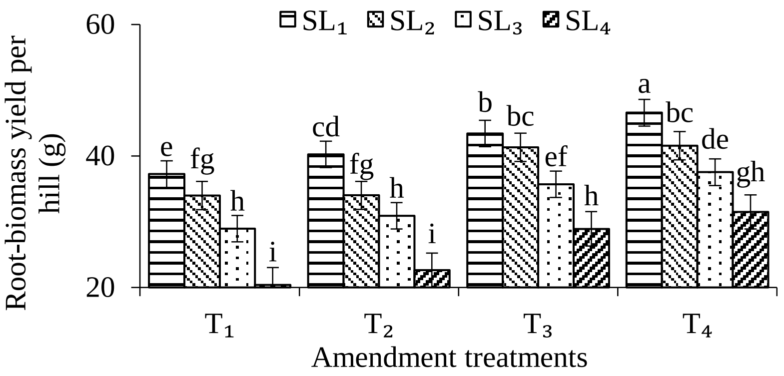


(a) Four salinity levels under four amendments irrespective of three rice cultivars

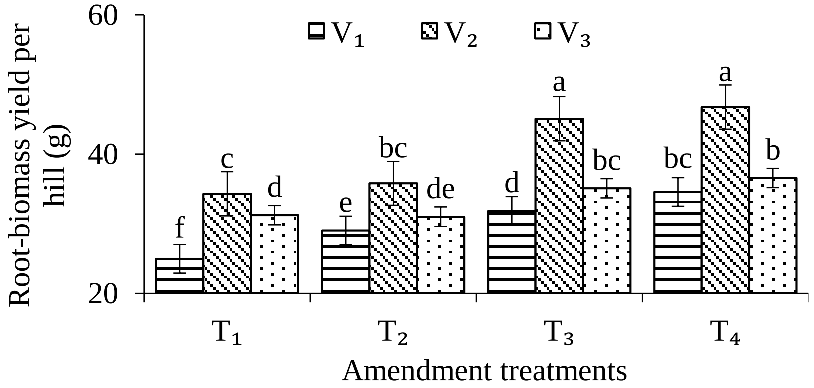


(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

Figure 11 Comparison of straw yield per hill (g) of rice

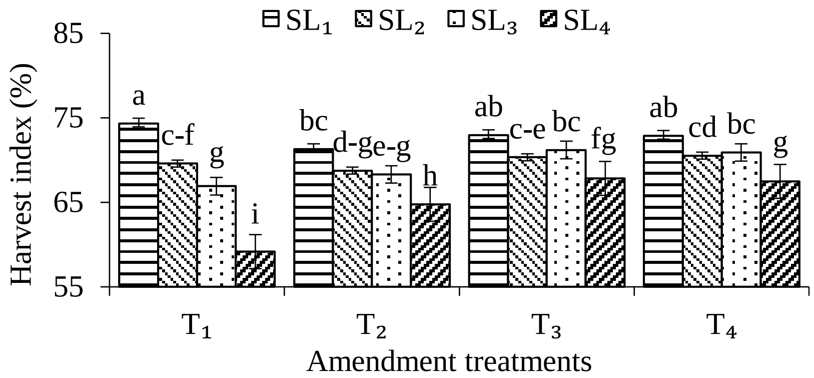


(a) Four salinity levels under four amendments irrespective of three rice cultivars

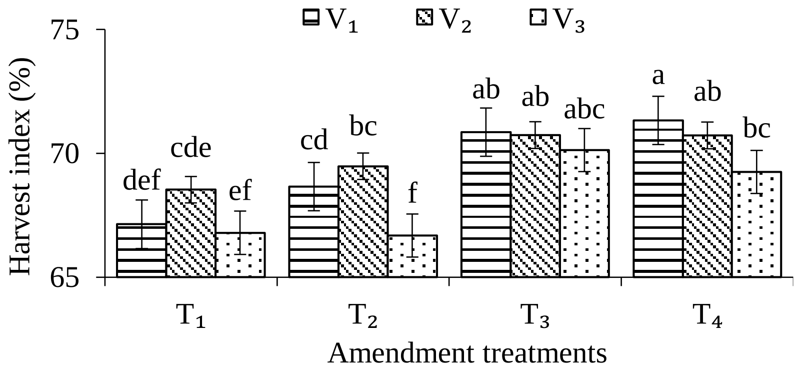


(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

Figure 12 Comparison of root-biomass yield of rice

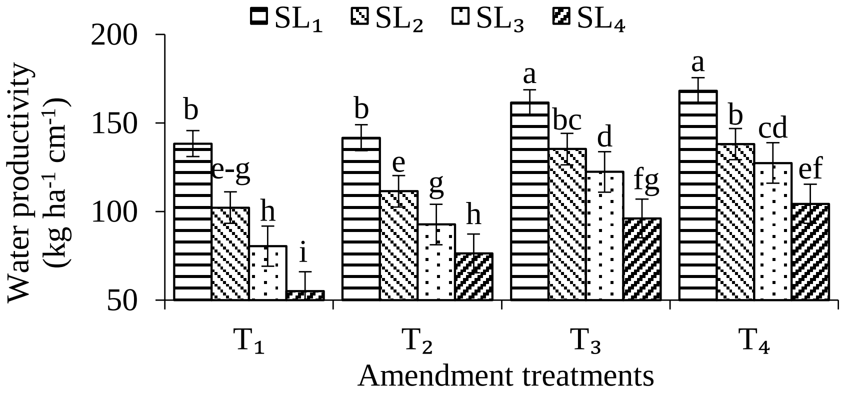


(a) Four salinity levels under four amendments irrespective of three rice cultivars

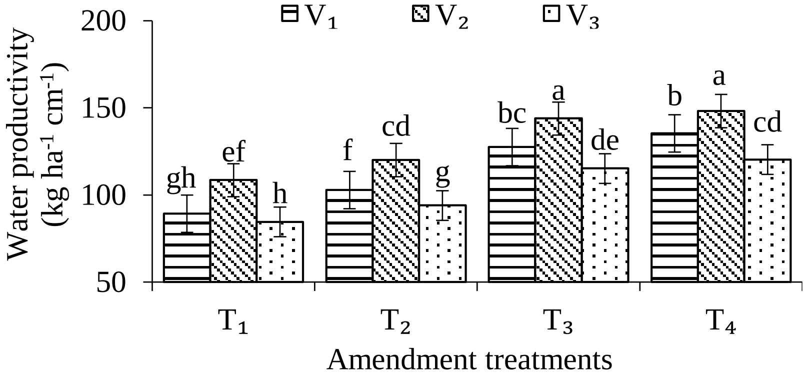


(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

Figure 13 Comparison of harvest index of rice



(a) Four salinity levels under four amendments irrespective of three rice cultivars



(b) genetic variation of the rice cultivars under the amendments irrespective of the salinity levels

Figure 14 Comparison of water productivity of rice

4 Discussion

4.1 Soil quality as affected by amendments

Irrigation with saline water makes the soils saline-sodic with elevated salt concentration, pH, exchangeable sodium and SAR (Table 3). Similar effects of saline-water irrigation were also observed by Abhayawickrama et al. (2020) and Zhang et al. (2019). Organic amendment (e.g., cow dung) adds organic matter to the soils (Table 3) and improves carbon content, porosity, water holding capacity, nutrient cycling, enzyme activities and biodiversity in saline soils (Bello et al., 2021). Gypsum controls the exchange of sodium (Na^+) for calcium (Ca^{2+}) on the clay surfaces and augments the Ca^{2+}/Na^+ ratio in the soil solution (Bello et al., 2021). It reduces soil pH (Table 3), maintains optimal K^+/Na^+ and Ca^{2+}/Na^+ ratios and provides crops with the required sulphur nutrition in saline soils (Ahmed et al., 2016; Abdel-Fattah, 2015; Capaldi et al., 2015). Application of gypsum in saline soils improves the physical (bulk density, aggregate stability and water infiltration) and chemical (pH, SAR, ESP, CEC, EC, nutrients availability and organic carbon) properties of the soils (Lastiri-Hernández et al., 2019; Wang et al., 2017; Kim et al., 2018; Alcívar et al., 2018), as well as enhances the soil microbial activity, biomass production and respiration (Alcívar et al., 2018). It also promotes a balanced concentration of electrolytes in the soil solution (Kim et al., 2016; Alcívar et al., 2018). Therefore, gypsum appears to be an effective soil amendment to reclaim saline soils and increase crop production.

4.2 Impacts of soil amendments on rice attributes exposed to salinity stress

Soil salinity affects the biochemical, physiological and morphological processes of plants (Lastiri-Hernández et al., 2019). These processes take place at osmotic and ionic phases (Al-Shareef and Tester, 2019). The osmotic phase follows soon after the uptake of excess salt and causes decline in water absorption capacity of the plants’ root systems. This phase also causes physiological changes and retards photosynthetic activity in the plants (Rahnama et al., 2010; Ahmad et al., 2018; Al-Shareef and Tester, 2019). The salinity at the osmotic phase ultimately stuns plant growth and reduces straw yield of rice (Table 4). The ionic phase is characterized by accumulation of Na^+ and Cl^- in the plant tissues that causes ion imbalance (higher Na^+/K^+ ratio), leaf necrosis and plant senescence earlier than the attainment of physiological maturity (Roy et al., 2014; Munns and Tester, 2008). The high Na^+ concentration hinders uptake of K^+ ions by the plant roots. The reduced K^+ ions hamper plant growth and development and cause lower productivity (James et al., 2011) of rice (Table 4). Under salinity stress, assimilate translocation from leaf to the grains decreases with the resulting reduction in biomass yield (Abdullah et al., 2001). Salinity stress also restricts cell division and cell elongation in plants (Hasanuzzaman et al., 2009; Islam et al., 2011), and significantly reduces plant vigor, growth, development and yield (Cheeseman, 2015). The high Na^+ accumulation makes the soils toxic and creates osmotic stress in plants, eventually leading to death of plant cells due to low water uptake (Ahanger et al., 2018). Consequently, application of high saline water (e.g., SL_4) drastically reduces the grain, straw and root yields, and water productivity of rice (Table 4).

Our results are in agreement with Cha-um et al. (2011), who reported that the level of sodium ions in Jasmine rice, grown in saline soil amended with gypsum and cowdung, was lower than those in the control (no use of soil amendment); the lower sodium ions resulted in higher water productivity. In addition to suppressing the salinity stress, gypsum also supplies sulfur and calcium to plants (Yildiz et al., 2017) and enhances their growth and yield (Bello et al., 2021). Intracellularly, Ca^{2+} also promotes a higher K^+/Na^+ ratio (Bello et al., 2021). Through the provision of sulphur, gypsum increases plants' tolerance and resistance to both biotic and abiotic stress factors by aiding the synthesis of proteins, chlorophyll-containing compounds as well as an increased uptake of phosphorus and nitrogen (Capaldi et al., 2015; Wiedenfeld, 2011).

4.3 Relative performance of different soil amendments

Table 7 compares the scores of performance of the tested rice cultivars and soil amendments in producing the attributes of rice under saline-water irrigation. Binadhan-10 performed significantly better than Binadhan-8 and BRRI dhan47 in producing the attributes of rice; only in case of harvest index, Binadhan-8 and Binadhan-10 performed alike. Amendment T_4 (cow-dung manure @ 6 t ha^{-1} and gypsum @ 150 kg ha^{-1}) was the most effective in improving the rice attributes except the plant height and unfilled grains, which were the most promising under T_3 (gypsum @ 150 kg ha^{-1}). Amendment T_3 and T_4 also performed alike in producing most of the rice attributes (Table 7). Thus, the integrated application of cowdung and gypsum in cultivating salt-sensitive and salt-tolerant crop varieties is a highly promising strategy in enhancing the productivity of saline soils as was also reported by Bello et al. (2021). Gypsum improves the physical and chemical characteristics of soils, as well as biomass and crop production (Lastiri-Hernández et al., 2019; Wang et al., 2017; Kim et al., 2016; Alcívar et al., 2018). It is also an effective amendment in soil reclamation (Lastiri-Hernández et al., 2019). Among various approaches for managing soil salinity, the integrated use of soil amendments was described as the most promising with significant impacts on food security (Cuevas et al., 2019).

Table 7 Scores of the performance of the rice cultivars (V_1, V_2 and V_3) and soil amendments (T_1, T_2, T_3 and T_4) in producing rice attributes. The tick (√) marks indicate the best performance and the approximately equal (≈) marks indicate statistically similar to the best performance

Rice attributes	Rice cultivars			Soil amendments			
	V_1	V_2	V_3	T_1	T_2	T_3	T_4
Plant height		√				√	
Total tillers per hill		√				√	≈
Effective tillers per		√				√	≈
Panicle length		√				√	√
Total grains		√				≈	√
Filled grains		√				√	√
Unfilled grains		√				√	
Thousand grain		√					√
Grain yield per hill		√					√
Straw yield per hill		√					√
Harvest index	≈	√				√	≈
Root-biomass yield		√					√
Water productivity		√					√

5 Conclusions

The coastal saline areas of Bangladesh having scarcity of fresh water but abundance of saline water could be brought under rice cultivation by conjunctive use of saline and fresh water to attain food security in future. Irrigation with fresh water at the critical salinity-sensitive growth stages and saline water at the less salinity-sensitive growth stages in association with an effective soil-amendment practice can be an effective way to cultivate salt-tolerant rice cultivars in those areas. Application of gypsum (150 kg ha^{-1}) or combined application of gypsum (150 kg ha^{-1}) and cowdung (6 t ha^{-1}) would be the effective soil amendments to reduce salinity stress on Binadhan-8, Binadhan-10 and BRRI dhan47 without significant yield loss; the combined application of the amendments performed the best. Gypsum is also a source of sulfur and calcium to plants, and affordable for the farmers in developing countries like Bangladesh. So, the combined application of these amendments augments the concentrations of nutrients available to plants. This study was done under controlled conditions with saline water irrigation in non-saline soil. Future study needs to verify the results at farmers' field in saline areas. However, it is expected that the results from the controlled and practical field experiments will be similar. So, the identified well-performing soil amendments are presumed to enhance rice production in coastal region having limited fresh water but abundant saline water.

Acknowledgments

This research was supported by the Bangladesh Agricultural Research Council (BARC) under its revenue funded in-country PhD scholarship program. The second author held this scholarship and was on deputation from the Bangladesh Institute of Nuclear Institute (BINA). Appreciation is extended to the BARC and BINA.

References

Abdel-Fattah, M. K. 2015. Potential use of halophytes in combination with gypsum to reclaim and restore saline-sodic soils in Egypt. *Malaysian Journal of Soil Science*, 19: 131–139.

Abdullah, Z., M. A. Khan, and T. J. Flowers. 2001. Causes of sterility in seed set of rice under salinity stress. *Journal of Agronomy and Crop Science*, 187(1): 25−32.

Abhayawickrama, B., D. Gimhani, N. Kottearachchi, V. Herath, D. Liyanage, and P. Senadheera. 2020. In Silico identification of QTL-based polymorphic genes as salt-responsive potential candidates through mapping with two reference genomes in rice. *Plants*, 9(2), 233.

Ahanger, M. A., M. N. Alyemeni, L. Wijaya, S. A. Alamri, P. Alam, M. Ashraf, and P. Ahmad. 2018. Potential of exogenously sourced kinetin in protecting Solanum lycopersicum from NaCl-induced oxidative stress through up-regulation of the antioxidant system, ascorbate-glutathione cycle and glyoxalase system. *PLoS One*, 13(9), p.e0202175.

Ahmad, P., M. A. Ahanger, P. Alam, M. N. Alyemeni, L. Wijaya, S. Ali, and M. Ashraf. 2018. Silicon (Si) supplementation alleviates NaCl toxicity in mung bean [Vigna radiata (L.) Wilczek] through the modifications of physio-biochemical attributes and key antioxidant enzymes. *Journal of Plant Growth Regulation*, 38: 70−82.

Ahmed, K., G. Qadir, A. R. Jami, A. I. Saqib, M. Q. Nawaz, M. A. Kamal, and E. Haq. 2016. Strategies for soil amelioration using sulphur in salt affected soils. *Cercetări Agronomice în Moldova*. Vol. XLIX, No. 3 (167)/2016: 5−16.

Alcívar, M., A. Zurita-Silva, M. Sandoval, C. Muñoz, and M. Schoebitz. 2018. Reclamation of saline–sodic soils with combined amendments: Impact on quinoa performance and biological soil quality. *Sustainability*, 10, 3083.

Al Khamisi, S. A., S. A. Prathapar, and M. Ahmed. 2013. Conjunctive use of reclaimed water and groundwater in crop rotations. *Agricultural Water Management*, 116: 228–234.

Al-shareef, O. N., and M. Tester. 2019. Plant salinity tolerance. In eLS; John Wiley & Sons Ltd.: Chichester, UK, pp. 1–6.

Analytical Software. 2019. Statistix 10: Data Analysis Software for Researchers. Analytical Software 2105 Miller Landing Rd, Tallahassee, FL 32312, USA.

Aref, F. 2013. Effect of saline irrigation water on yield and yield components of rice (*Oryza sativa* L.). *African Journal of Biotechnology*, 12(22): 3505–3508.

Bello, S. K., A. H. Alayafi, S. G. Al-Solaimani, and K. A. M. Abo-Elyousr. 2021. Mitigating soil salinity stress with gypsum and bio-organic amendments: A review. *Agronomy*, 11(9): 1735.

Capaldi, F. R., P. L. Gratão, A. R. Reis, L. W. Lima, and R. A. Azevedo. 2015. Sulfur metabolism and stress defense responses in plants. *Tropical Plant Biology*, 8: 60−73.

Chahal, S. S., O. P. Choudhary, and M. S. Mavi. 2017. Organic amendments decomposability influences microbial activity in saline soils. *Archives of Agronomy and Soil Science*, 63(13): 1875–1888.

Cha-um, S., Y. Pokasombat, and C. Kirdmanee. 2011. Remediation of salt-affected soil by gypsum and farm yard manure importance for the production of Jasmine rice. *Australian Journal of Crop Science*, 5(4): 458−465.

Cheeseman, J. M. 2015. The evolution of halophytes, glycophytes and crops, and its implications for food security under saline conditions. *New Phytologist*, 206(2): 557−570.

Choudhary, O. P., A. S. Josan, M. S. Bajwa, and M. L. Kapur. 2004. Effect of sustained sodic and saline-sodic irrigation and application of gypsum and farmyard manure on yield and quality of sugarcane under semi-arid conditions. *Field Crops Research*, 87(2-3): 103–116.

Cuevas, J., I. N. Daliakopoulos, F. del Moral, J. J. Hueso, and I. K. Tsanis. 2019. A review of soil-improving cropping systems for soil salinization. *Agronomy*, 9(6), p.295.

Dutta, T., M. M. Rahman, M. S. U. Bhuiya, and M. A. Kader. 2014. Use of organic amendment for amelioration of salinity stress in transplanted aman rice cv. BRRI dhan41. *Journal of Natural and Social Sciences*, 2: 82−94.

FAO (Food and Agriculture Organization). 2021. Global Map of Salt-Affected Soils. Available at: https://www.fao.org/3/cb7247en/cb7247en.pdf. Accessed 28 April 2022.

Gandahi, A. W., A. Kubar, M. S. Sarki, N. Talpur, and M. Gandahi. 2017. Response of conjunctive use of fresh and saline water on growth and biomass of cotton genotypes. *Journal of Basic and Applied Sciences*, 13: 326–334.

Gonçalo Filho, F, N. da Silva Dias, S. R. P. Suddarth, J. F. S. Ferreira, R. G. Anderson, C. dos Santos Fernandes, R. B. de Lira, M. F. Neto, and C. R. Cosme. 2019. Reclaiming tropical saline-sodic soils with gypsum and cow manure. *Water*, 12(1): 57.

Gupta, B., and B. Huang. 2014. Mechanism of salinity tolerance in plants: physiological, biochemical, and molecular characterization. *International Journal of Genomics*, 2014: 701596.

Hasanuzzaman, M., M. Fujita, M. N. Islam, K. U. Ahmed, and K. Nahar. 2009. Performance of four irrigated rice varieties under different levels of salinity stress. *International Journal of Integrative Biology*, 6(2): 85−90.

Hoque, M. Z., and M. E. Haque. 2016. Impact of climate change on crop production and adaptation practices in coastal saline areas of Bangladesh. *International Journal of Advanced Research*, 2(1): 10–19.

Iqbal, M. T., R. G. Joergensen, C. Knoblauch, R. Lucassen, Y. Singh, C. Watson, and F. Wichern. 2016. Rice straw addition does not substantially alter microbial properties under hypersaline soil conditions. *Biology and Fertility of Soils*, 52(6): 867–877.

Islam, M. T., P. C. Sharma, R. K. Gautam, D. Singh, S. Singh, B. Panesar, and S. Ali. 2011. Salt tolerance in parental lines of rice hybrids through physiological attributes molecular markers. *International Journal of Experimental Agriculture*, 2(1): 1–7.

James, R. A., C. Blake, C. S. Byrt, and R. Munns. 2011. Major genes for Na+ exclusion, Nax1 and Nax2 (wheat HKT1; 4 and HKT1; 5), decrease Na^+ accumulation in bread wheat leaves under saline and waterlogged conditions. *Journal of Experimental Botany*, 62(8): 2939−2947.

Karim, M. R. 2007. Effect of Salinity on Growth, Yield and Yield Attributes of Rice Cultivars. M.S. thesis, Department of Crop Botany, Bangladesh Agricultural University, Bangladesh.

Khattak, S. G., I. U. Haq, A. Malik, M. J. Khattak, and M. J. Naveedullah. 2007. Effect of various levels of gypsum application on the reclamation of salt affected soil grown under rice followed by wheat crop. *Sarhad Journal of Agriculture*, 23: 675–680.

Kim, H. S., K. R. Kim, S. H. Lee, A. Kunhikrishnan, W. I. Kim, and K. H.Kim. 2018. Effect of gypsum on exchangeable sodium percentage and electrical conductivity in the Daeho reclaimed tidal land soil in Korea—a field scale study. Journal of Soils and Sediments, 18: 336−341.

Kivi, S. T., and R. T. Bailey. 2017. Modeling sulfur cycling and sulfate reactive transport in an agricultural groundwater system. *Agricultural Water Management*, 185: 78–92.

Lastiri-Hernández, M. A., D. Alvarez-Bernal, K. Bermúdez-Torres,G. C. Cárdenas, and L. F. Ceja-Torres. 2019. Phytodesalination of a moderately saline soil combined with two inorganic amendments. *Bragantia*, 78: 579–586.

Leogrande, R., and C. Vitti. 2019. Use of organic amendments to reclaim saline and sodic soils: a review. *Arid land Research and Management*, 33(1): 1–21.

Mahmoodabadi, M., N. Yazdanpanah, L. R. Sinobas, E. Pazira, and A. Neshat. 2013. Reclamation of calcareous saline sodic soil with different amendments (I): Redistribution of soluble cations within the soil profile. *Agricultural Water Management*, 120: 30–38.

McFarlane, D. J., R. J. George, E. G. Barrett-Lennard, and M. Gilfedder. 2016. Salinity in dry land agricultural systems: challenges and opportunities. In *Innovations in Dryland Agriculture*, eds. M. Farooq, and K. Siddique, ch. 19, 521–547. : Gewerbestrasse 11, 6330 Cham, Switzerland: Springer, Cham.

Mojid, M. A., and A. Z. Hossain. 2013. Conjunctive use of Saline and fresh water for irrigating wheat (*Triticum aestivum* L.) at different growth stages. *Agriculturists*, 11(1): 15–23.

Munns, R. and M. Tester. 2008. Mechanisms of salinity tolerance. *Annual Review of Plant Biology*, 59: 651–681.

Nan, J., X. Chen, C. Chen, M. S. Lashari, J. Deng, and Z. Du. 2016. Impact of flue gas desulfurization gypsum and lignite humic acid application on soil organic matter and physical properties of a saline-sodic farmland soil in Eastern China. *Journal of Soils and Sediments*, 16: 2175–2185.

Oo, A. N., P. Banterng, A. Polthanee, and V. Trelo-Ges. 2010. The effect of different fertilizers management strategies on growth and yield of upland black glutinous rice and soil property. *Asian Journal of Plant Sciences*, 9(7): 414–419.

Pang, Q., S. Chen, S. Dai, Y. Chen, Y. Wang, and X. Yan. 2010. Comparative proteomics of salt tolerance in Arabidopsis thaliana and Thellungiella halophila. *Journal of Proteome Research*, 9(5): 2584–2599.

Parvin, G. A., M. H. Ali, K. Fujita, M. A. Abedin, U. Habiba, and R. Shaw. 2017. Land use change in southwestern coastal Bangladesh: consequence to food and water supply. In *Land Use Management in Disaster Risk Reduction*, eds. M. Banba, and R. Shaw, ch. 20, 381–401. Tokyo, Japan: Springer.

Rad, H. E., F. Aref, and M. Rezaei. 2012. Response of rice to different salinity levels during different growth stages. *Research Journal of Applied Sciences, Engineering and Technology*, 4(17): 3040–3047.

Rahman, M. A., T. Ahmed, and M. A. Mojid. 2020. Coupled irrigation–drainage management practice for HYV rice cultivation with saline-irrigation water: evidence from lysimeter experiment. *Agricultural Science*, 2(1): 95–108.

Rahman, S., M. R. H. Sarker, and M. Y. Mia. 2017. Spatial and temporal variation of soil and water salinity in the south-western and south-central coastal region of Bangladesh. *Irrigation and Drainage*, 66(5): 854–871.

Rahnama, A., R. A. James, K. Poustini, and R. Munns. 2010. Stomatal conductance as a screen for osmotic stress tolerance in durum wheat growing in saline soil. *Functional Plant Biology*, 37(3): 255–263.

Rana, M. S. 2007. Effect of salinity on growth and photosynthetic potential in some advanced rice lines. M.S. thesis, Department of Crop Botany, Bangladesh Agricultural University, Bangladesh.

Roy, S. J., S. Negrão, and M. Tester. 2014. Salt resistant crop plants. *Current Opinion in Biotechnology*, 26: 115–124.

Sexcion, F. S. H., J. A. Egdane, A. M. Ismail, and M. L. Dionisio-Sese. 2009. Morphophysiological traits associated with tolerance of salinity during seedling stage in rice (*Oryaz sativa* L.). *Philippine Journal of Crop Science*, 34(2): 27–37.

Shaaban, M., M. Abid, and R. A. I. Abu-Shanab. 2013. Ameliration of salt affected soil in rice paddy system by application of organic and inorganic amendments. *Plant Soil Environment*, 59(5): 227−233.

Siam, M. Z., S. S. Hossain, A. K. Hassan, and M. A. Kader. 2015. Amelioration of salinity stress on transplant Aman rice through green manure and gypsum. *Bangladesh Agronomy Journal*, 17: 1−10.

Singh, A. 2014a. Conjunctive use of water resources for sustainable irrigated agriculture. *Journal of Hydrology*, 519: 1688–1697.

Singh, A. 2014b. Groundwater resources management through the applications of simulation modeling: A review. *Science of the Total Environment*, 499: 414–423.

SRDI (Soil Resources Development Institute). 2016. Annual Report 2015–2016. Ministry of Agriculture. Dhaka, Bangladesh: Government of the People’s Republic of Bangladesh, Dhaka, Bangladesh.

Ullah, W., and A. Bhatti. 2007. Physico-chemical properties of soils of Kohat and Bannu districts NWFP Pakistan. *Journal of the Chemical Society of Pakistan*, 29: 20–25.

US Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. US Department of Agriculture Handbook 60, Washington, DC.

Wang, S. J., Q. Chen, Y. Li, Y. Q. Zhuo, and L. Z. Xu. 2017. Research on saline-alkali soil amelioration with FGD gypsum. *Resources, Conservation and Recycling*, 121: 82–92.

Wiedenfeld, B. 2011. Sulfur application effects on soil properties in a calcareous soil and on sugarcane growth and yield. *Journal of Plant Nutrition*, 34(7): 1003–1013.

Yildiz, O., E. Altundağ, B. Çetin, Ș. T. Güner, M. Sarginci, and B. Toprak. 2017. Aeorestation restoration of saline-sodic soil in the Central Anatolian Region of Turkey using gypsum and sulfur. *Silva Fennica*, 51(1B): 1–17.

Yu, J., Z. Wang, F. X. Meixner, F. Yang, H. Wu, and X. Chen. 2010. Biogeochemical characterizations and reclamation strategies of saline sodic soil in Northeastern China. CLEAN-Soil Air Water, 38(11): 1010–1016.

Zhang, W. W., W. A. N. G. Chong, X. U. E. Rui, and L. J. Wang. 2019. Effects of salinity on the soil microbial community and soil fertility. *Journal of Integrative Agriculture*, 18(6): 1360–1368.