CROP RESIDUE AMENDMENTS IMPROVE NUTRIENT UPTAKE AND Na^+/K^+ HOMEOSTASIS IN RICE UNDER COMBINED SALT AND WATER DEFICIT STRESS

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ABSTRACT

Background: Soil salinity and water scarcity are significant constraints to rice production in coastal agroecosystems, where plants frequently encounter combined salt and moisture stress, particularly in the dry season. This study evaluated the effects of crop residue-based organic amendments such as rice straw compost (RSC), sawdust (SD), rice husk (RH), and mustard seed meal (MSM) on nutrient uptake and Na^+/K^+ homeostasis in two contrasting rice genotypes, BRRI Dhan 28 (salt-sensitive) and BRRI Dhan 47 (salt-tolerant), under full and deficit irrigation regimes. **Methods:** A split-split plot field experiment was conducted during the dry season in salt-affected coastal soils of Khulna, Bangladesh. **Findings:** Organic amendments significantly ($p \leq 0.05$) improved the uptake of macro- (N, P, K, S, Ca, Mg) and micronutrients (Fe, Mn, Zn) in both genotypes. The MSM enhanced N, Ca, and Mg accumulation, while RSC and SD effectively increased K^+ and S uptake. All amendments markedly reduced the Na^+/K^+ ratio, improving ionic balance and alleviating salinity-induced toxicity. Correlation analyses indicated strong positive associations among key nutrients and significant negative relationships between Na^+/K^+ ratios and nutrient contents, underscoring the role of amendments in optimizing nutrient dynamics. **Conclusion:** These findings demonstrate that integrating crop residue-based organic amendments into salt-affected coastal soils enhances nutrient availability, maintains ionic homeostasis, and mitigates combined salt and water deficit stress in rice. Adopting such sustainable practices offers a promising pathway for improving soil health, boosting rice productivity, and strengthening climate resilience in vulnerable coastal agroecosystems.

KEYWORDS: salt stress; water deficit stress; organic amendment; rice; nutrient contents; Na^+/K^+ homeostasis

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Introduction

Global agriculture faces growing threats from soil salinisation and water scarcity. Salt-affected soils now cover a significant portion of arable land, severely limiting crop productivity and resilience, especially in rice, the staple food for billions, notably in coastal regions (Ivushkin *et al.*, 2019; Khanom, 2016; Rezvi *et al.*, 2023; Singh, 2022). Salinity severely constrains rice productivity by disrupting physiological processes and nutrient uptake, impairing growth and yield (Zheng *et al.*, 2023; Zörb *et al.*, 2019). Soil salinization causes osmotic and ionic stress, disrupting essential nutrient balances and disturbing Na^+/K^+ homeostasis in rice plants (Hussain *et al.*, 2021; Liu *et al.*, 2024; Sackey *et al.*, 2025). Water scarcity further exacerbates the adverse effects of salinity by limiting nutrient availability and transport, as reduced soil moisture restricts root function and intensifies salt accumulation near the root zone (Li *et al.*, 2024; Munns, 2002). Therefore, rice plants in coastal saline environments often face the combined stress of salt and water deficits, especially during the dry season, which presents a significant obstacle to sustainable crop production.

In the early phase, salinity-induced osmotic stress restricts water absorption, reducing cell turgor, stomatal conductance, and photosynthesis, which stifles growth and yield (Munns and Tester, 2008; Saleem *et al.*, 2025). As salinity persists, toxic levels of Na^+ and Cl^- accumulate, causing ionic imbalance, impaired enzyme activity, and oxidative damage (Li *et al.*, 2024). A key issue of salt stress in rice is its disruption of nutrient uptake. High Na^+ levels compete with essential cations like K^+, Ca^{2+}, and Mg^{2+}, impeding their uptake and affecting metabolic functions. (Coca *et al.*, 2023). Disruptions in micronutrient uptake, like Fe, Mn, and Zn, further limit photosynthesis and enzymatic activities (Sackey *et al.*, 2025). Maintaining a high ratio of K^+ to Na^+ in the cytosol is central to rice salt tolerance (Almeida *et al.*, 2017). Rice deploys specific transporters such as OsHKT1;5, OsHAK21, and OsAKT1 along with osmotic adjustments to preserve this ionic equilibrium (Fuchs *et al.*, 2005; Kobayashi *et al.*, 2017; Shen *et al.*, 2015).

Addressing these constraints requires effective soil management strategies that improve nutrient availability, promote Na^+/K^+ homeostasis, and mitigate the harmful effects of salinity and drought. Incorporating organic amendments has gained attention as an eco-friendly and cost-effective intervention for salinity alleviation, improving soil physical properties, increasing organic carbon content, and promoting beneficial microbial activity (Leogrande and Vitti, 2019). These changes enhance water retention and nutrient cycling, thereby stabilizing nutrient uptake and reducing Na^+ toxicity by improving soil hydraulic properties and supporting salt leaching (Hoque *et al.*, 2022).

While previous studies have shown the benefits of organic amendments in improving soil quality and supporting plant growth under saline conditions, their specific effects on nutrient uptake and Na^+/K^+ homeostasis during combined salt and water deficit stress are not fully understood, particularly in salt-affected coastal agroecosystems (Wei *et al.*, 2023). Furthermore, genotypic variation in rice response further complicates management recommendations, with salt-sensitive and salt-tolerant varieties exhibiting distinct nutrient assimilation patterns under stresses (Leon *et al.*, 2015).

This study investigates the impact of amending salt-affected coastal soils with different crop residue-based organic materials, such as rice straw compost (RSC), sawdust (SD), rice husk (RH), and mustard seed meal (MSM), on nutrient uptake and Na^+/K^+ balance in two contrasting rice genotypes under full and deficit irrigation regimes. The objective is to elucidate how organic amendments influence nutrient dynamics and Na^+/K^+ homeostasis in rice subjected to combined salt and moisture stress, aiming to identify effective practices for sustaining productivity in salt-affected coastal areas.

Materials and Methods

Experimental site and climatic conditions

The field experiment was conducted on a salt-affected coastal paddy field at Batiaghata (GPS: 22°43'49.4"N, 89°28'00.1"E), Khulna, Bangladesh, from January 2020 to April 2020 during the dry season. The site physiographically belongs to the High Ganges Alluvium Floodplain and is part of Agroecological Zone (AEZ)-13, known as the Ganges Tidal Floodplain (FAO, 1988). The site is situated in the south-western coastal region of Bangladesh and is characterised by a humid subtropical climate with distinct seasonal variation. The mean annual air temperature is approximately 26.4 °C, ranging from an average minimum of 11.0 °C in January to a maximum of 37.7 °C in May. The area receives an average annual rainfall of about 1,808 mm, with seasonal distribution as follows: pre-monsoon (March–May) 313 mm, monsoon (June–September) 1,248 mm, and post-monsoon (October–November) 195 mm, while the winter months (December–February) receive negligible rainfall. Relative humidity remains high throughout the year, averaging 79.4%, and typically peaks during the monsoon months (BBS, 2015). The region is prone to seasonal soil salinisation due to tidal intrusion, reduced freshwater inflow, and seawater seepage, particularly during the dry season, affecting crop production and land use patterns (Dasgupta *et al.*, 2015; SRDI, 2010). **Figure 1.** depicts the weather conditions experienced by the site during the experiment.

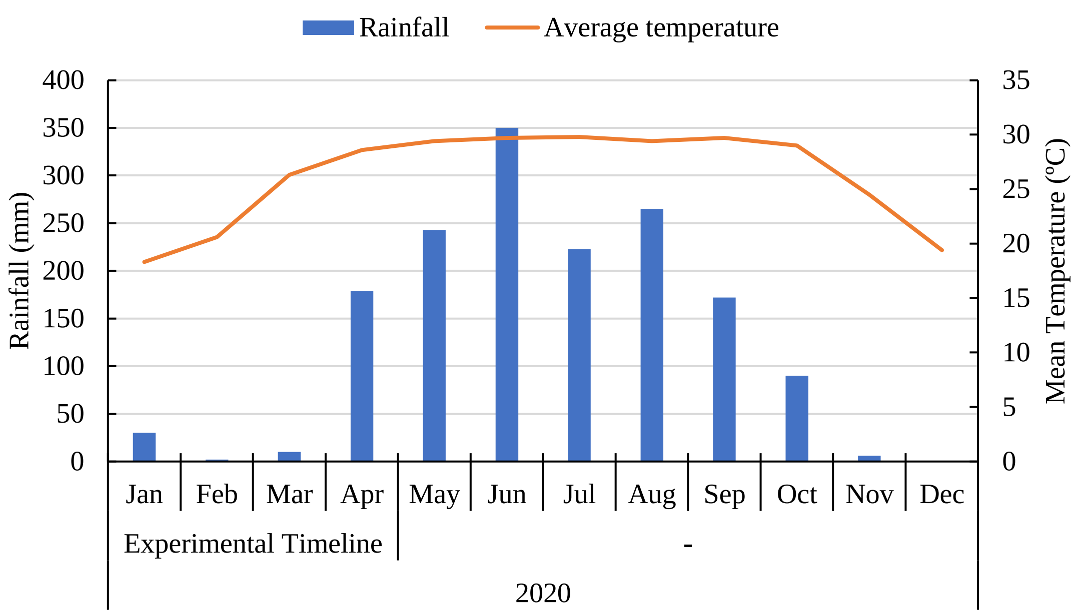


Figure 1. Monthly rainfall (mm) and average temperature (°C) experienced by the experimental site during the experiment (Source: Bangladesh Meteorological Department data, 2020)

Soil, organic amendments, and planting materials

The soil at the experimental site is part of the Bajoa soil series, characterised by a medium-lowland environment and salinity. The physical and chemical properties of the initial soil are presented in **Table 1**. The soil was amended with four indigenous crop residue-based organic amendments: rice straw compost (RSC), sawdust (SD), rice husk (RH), and mustard seed meal (MSM). The composition and nutrient content of each amendment are detailed in **Table 1**. This study used two rice cultivars—BRRI Dhan 28 and BRRI Dhan 47—as test crops. Both genotypes were developed by the Bangladesh Rice Research Institute, with BRRI Dhan 28 being salt sensitive and BRRI Dhan 47 salt-tolerant.

Irrigation water

The experimental field was irrigated with groundwater from a nearby source. The chemical properties of the irrigation water used in the field experiment were monitored monthly throughout the study and are shown in **Table 2**. Two different soil moisture levels (ML), deficit irrigation (ML_{70}) and full irrigation (ML_{100}), were applied in the experiment. The irrigation treatments were maintained from 30 days after seedling transplantation until the crops reached maturity by providing the necessary water. Full irrigation was achieved through frequent watering, resulting in 4-5 cm of standing water in the respective plots. The deficit irrigation involved supplying 70% of the water required for full irrigation. For each irrigation event, the volume of water needed for full irrigation was multiplied by 0.7 to calculate the required volume for deficit irrigation.

Table 1. Physical and chemical properties of the initial soil and organic amendments

Properties	Initial soil	Rice straw compost (RSC)	Sawdust (SD)	Rice husk (RH)	Mustard seed meal (MSM)
Textural class	Silty clay loam	-	-	-	-
pH	7.8	6.75	7.6	6.33	5.51
EC (dS m^{-1})	8.2	1.38	0.69	1.27	1.0
Organic carbon (%)	0.78	36.5	33.15	29.5	49.3
CEC ($cmol_c$ kg^{-1})	19.5	-	-	-	-
Total N (%)	-	2.04	0.4	0.55	5.8
Total P (%)	-	0.14	0.05	0.39	1.36
Total K (%)	-	0.48	0.34	0.16	1.9
Total S (%)	-	0.15	0.007	0.04	0.51
C/N ratio	5.57	17.89	82.88	53.64	8.5
Available N (mg kg^{-1})	43	-	-	-	-
Available P (mg kg^{-1})	11.25	-	-	-	-
Exchangeable K ($cmol_c$ kg^{-1})	0.34	-	-	-	-
Available S (mg kg^{-1})	674.48	-	-	-	
$SAR_{1:5}$ (mmol $L^{-1})^{0.5}$	7.40	-	-	-	-
ESP (%)	20.0	-	-	-	-

Table 2. Chemical properties of irrigation water used in the field experiment

pH	EC (dS m^{-1})	Na^+ (meq L^{-1})	Ca^{2+} (meq L^{-1})	Mg^{2+} (meq L^{-1})	SAR (mmol $L^{-1})^{0.5}$
7.35 ± 0.16	1.46 ± 0.19	4.26 ± 0.18	2.37 ± 0.05	3.12 ± 0.40	2.58 ± 0.13

The values are the average of four measurements (n = 4) taken across different months, with the standard deviation included.

Experimental design

The experiment was arranged in a split-split plot design with a randomised complete block layout, replicated three times. Each main plot consists of 13 subplots (2m × 2m), and each subplot is divided into sub-subplots. The main plots were assigned for irrigation treatments, full irrigation (ML_{100}) and deficit irrigation (ML_{70}), respectively. In the subplots of the main plots, selected rates of RSC, SD, RH, and MSM were randomly assigned at rates of 0, 5, 10, and 15 t ha^{-1}, and the rice varieties were assigned to sub-subplots. The treatment combinations are indicated in the paper by subscripting the rate to the abbreviation of the amendments, such as ML_{100} (full irrigation, salt-stressed control), ML_{70} (deficit irrigation, salt- and water-deficit stressed control), RSC_5ML_{100}, $RSC_{10}ML_{100}$, $RSC_{15}ML_{100}$, SD_5ML_{100}, $SD_{10}ML_{100}$, $SD_{15}ML_{100}$, RH_5ML_{100}, $RH_{10}ML_{100}$, $RH_{15}ML_{100}$, MSM_5ML_{100}, $MSM_{10}ML_{100}$, $MSM_{15}ML_{100}$, RSC_5ML_{70}, $RSC_{10}ML_{70}$, $RSC_{15}ML_{70}$, SD_5ML_{70}, $SD_{10}ML_{70}$, $SD_{15}ML_{70}$, RH_5ML_{70}, $RH_{10}ML_{70}$, $RH_{15}ML_{70}$, MSM_5ML_{70}, $MSM_{10}ML_{70}$, $MSM_{15}ML_{70}$. A 30 cm drain was installed between the main plots to manage the irrigation water supply. Each sub-plot was surrounded by a 10 cm thick earthen boundary with a standard spacing of 20 cm between plots to prevent contamination from neighboring sub-plots. All subplots received an equal amount of inorganic fertiliser. Nitrogen was applied from Urea at a rate of 120 kg ha^{-1}, split into two doses: two-thirds as a basal dose and one-third as a top dressing at the active tillering stage. Phosphate from Triple Super Phosphate (TSP) was applied at 26 kg ha^{-1}, and potassium from Muriate of Potash (MoP) at 33 kg ha^{-1}, both as basal doses. Organic amendments derived from crop residues were thoroughly incorporated into the soil of each subplot two weeks prior to transplantation. The two rice genotypes were assigned to the sub-subplots of each subplot. The distance from hill to hill was 15 cm, and from row to row was 20 cm, with three seedlings transplanted per hill. Each variety's border row around the plot was used as a guard row, while the remaining rows were used for sampling plants.

Initial soil samples before the start of the experiment were collected from 0 to 20 cm below the surface at various points in the field using a soil core sampler and composited for physical and chemical analysis as detailed below. These samples were air-dried, crushed, and passed through a 2 mm sieve. At maturity, rice straw was collected from each sub-subplot using three randomly placed 0.25 m × 0.25 m quadrats. Plants within each quadrat were cut at ground level, and straw was separated from panicles. Quadrats from the same plot were composited, washed with deionised water, air dried, oven-dried at 65 °C to constant weight, ground to pass through a 0.5 mm sieve, and stored in airtight containers for nutrient analysis.

Physical and chemical analysis

The textural class of the soil was determined according to the United States Department of Agriculture (USDA) using Marshall's triangular coordinates after separating and determining the percentage of soil particles by the Hydrometer Method. The soil was treated with 30% H_2O_2 to oxidise organic fractions, and a sodium hexametaphosphate solution was used to remove other cementing agents (Gee and Bauder, 1986). Soil pH was measured using a HANNA Instruments HI 2211 pH/ORP Meter with a soil-to-water ratio of 1:2.5, shaken for 30 minutes at 120 rpm (Jackson, 1958). Electrical conductivity (EC) was determined with an EUTECH Instruments EC meter from saturated paste extract (Richards, 1954). The organic carbon was determined through wet combustion using $K_2Cr_2O_7$ in an acidic medium (Walkley and Black, 1934). The plant available N in the soil was extracted with 2M KCl and determined using the steam distillation method (Keeney and Nelson, 1982). The plant available P in soil was extracted by 0.5M $NaHCO_3$ at pH 8.5. The phosphorus was then determined colorimetrically by a PG spectrophotometer at 880 nm wavelength after developing a blue color with sulfuric acid, ammonium molybdate, ascorbic acid, and potassium antimony tartrate (Olsen and Sommers, 1982). The plant available S in the soil was extracted by a 0.7N sodium acetate + 0.54N acetic acid solution at pH 4.8. Sulfur was determined by the turbidity developed by suspended $BaSO_4$ using Tween-80 stabilizer. A spectrophotometer measured the turbidity at a 420 nm wavelength (Tan, 2005). The cation exchange capacity (CEC) of soil was determined by extracting it with 1N ammonium acetate (pH 7.0) and replacing the ammonium in the exchange complex with 1M NaCl (pH 7.0). The displaced ammonium was distilled with 40% NaOH, and the ammonia was collected in 4% boric acid with a mixed indicator. The ammonia was titrated with standardized 0.01 N H_2SO_4 (Tan, 2005). The exchangeable K^+ and Na^+ were extracted with 1N neutral ammonium acetate solution and determined by flame photometer (Biobase Flame Photometer BK-FP64).

Exchangeable sodium percentage (ESP) was calculated by **Eq. 1** (Richards, 1954).

$$ESP = \frac{\text{Exchangeable } Na^+ \ (cmol_c\ kg^{-1})}{CEC\ (cmol_c\ kg^{-1})} \times 100 \quad \textbf{(Eq. 1)}$$

The sodium absorption ratio was calculated using **Eq. 2** from the extract of a 1:5 soil-to-water ratio (Richards, 1954).

$$SAR = \frac{Na^+}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}} \quad \textbf{(Eq. 2)}$$

Na^+, Ca^{2+}, and Mg^{2+} were expressed in meq L^{-1}, and $SAR_{1:5}$ was expressed as $(mmol\ L^{-1})^{0.5}$.

The grounded plant sample was digested employing concentrated HNO_3-$HClO_4$ acid. The total P content was measured colorimetrically using a spectrophotometer at a wavelength of 430 nm after developing a yellow complex from the digest with vanadomolybdate (Jackson, 1958). Total sulfur in plant tissue was determined from the HNO_3-$HClO_4$ acid digest by developing turbidity. The Na and K were measured with flame photometry, and Ca, Mg, Fe, Zn, and Mn were determined by atomic absorption spectrophotometry (PerkinElmer PinAAcle 500 Flame Atomic Absorption Spectrophotometer). Total nitrogen in the plant tissue was determined using the Regular Kjeldahl Method, which involves H_2SO_4 digestion followed by steam distillation with NaOH. The ammonia collected in boric acid was then quantified titrimetrically (Bremner and Mulvaney, 1982). The Na^+/K^+ ratio in plant tissue was calculated by dividing Na content by K content. The total nutrient contents of organic amendments were determined following the same methods as the plant sample. The pH and EC of the amendments were measured from suspensions made with 1:2.5 and 1:5 amendment-to-water ratios, respectively. The organic C content of the amendments was determined following the same method as that of the soil. The pH, EC, Na, Ca, and Mg concentrations of irrigation water were determined using the methods described above. The SAR of irrigation water was calculated using **Eq. 2**.

Data analysis

The effect of organic amendments, irrigations, and their interaction on the nutrient contents in rice was assessed by a general linear model analysis. The significant differences ($p \leq 0.05$) among treatments were identified by performing Tukey's Honestly Significant Difference (HSD) test. The normality and equivariance test were conducted for the model's residuals using Anderson-Darling and Levene's test, respectively. The average of replicates is presented in all the tables and figures for each parameter. The error bar in the figures indicates the standard deviation of the three replicates. Pearson's correlation identified the association of nutrient contents and Na^+/K^+ ratio in the mature rice tissue. All these statistical tests were conducted using the Minitab Statistics-20.

Results

Nitrogen (N) content

Nitrogen content in rice shoots responded significantly ($p < 0.001$) to organic amendments, irrigation regimes, and their interactions (**Table 3**). Across both genotypes, MSM consistently delivered the highest N accumulation (**Figure 2**). In BRRI Dhan 28, MSM at 10 t ha^{-1} under full irrigation increased N content to 13.02 g kg^{-1}, more than a 220% improvement over unamended deficit-irrigated controls (4.06 g kg^{-1}). Similarly, BRRI Dhan 47 exhibited peak N content (14.81 g kg^{-1}) with MSM at 15 t ha^{-1} under full irrigation, a 210% increase compared to its stressed control (4.77 g kg^{-1}). These results suggest that MSM is highly effective among the four crop residues at sustaining N assimilation under combined salinity and water deficit stress.

Phosphorus (P) content

Phosphorus uptake improved significantly ($p < 0.001$) with organic amendments, particularly under full irrigation (**Table 3**). In BRRI Dhan 28, MSM at 10 t ha^{-1} increased P uptake to 1.08 g kg^{-1}, a 337% gain relative to unamended dual-stressed plants (0.25 g kg^{-1}). Comparable enhancements were observed with SD (0.99 g kg^{-1}) and RH (0.96 g kg^{-1}) at 15 t ha^{-1} under full irrigation. In BRRI Dhan 47, MSM at 10 t ha^{-1} under full irrigation yielded the highest P content (1.55 g kg^{-1}). At the same time, SD and RH also significantly enhanced P accumulation (**Figure 3**). MSM and SD effectively alleviate P deficiency, which is typically aggravated under dual stress of salinity and water deficiency (ML_{70}).

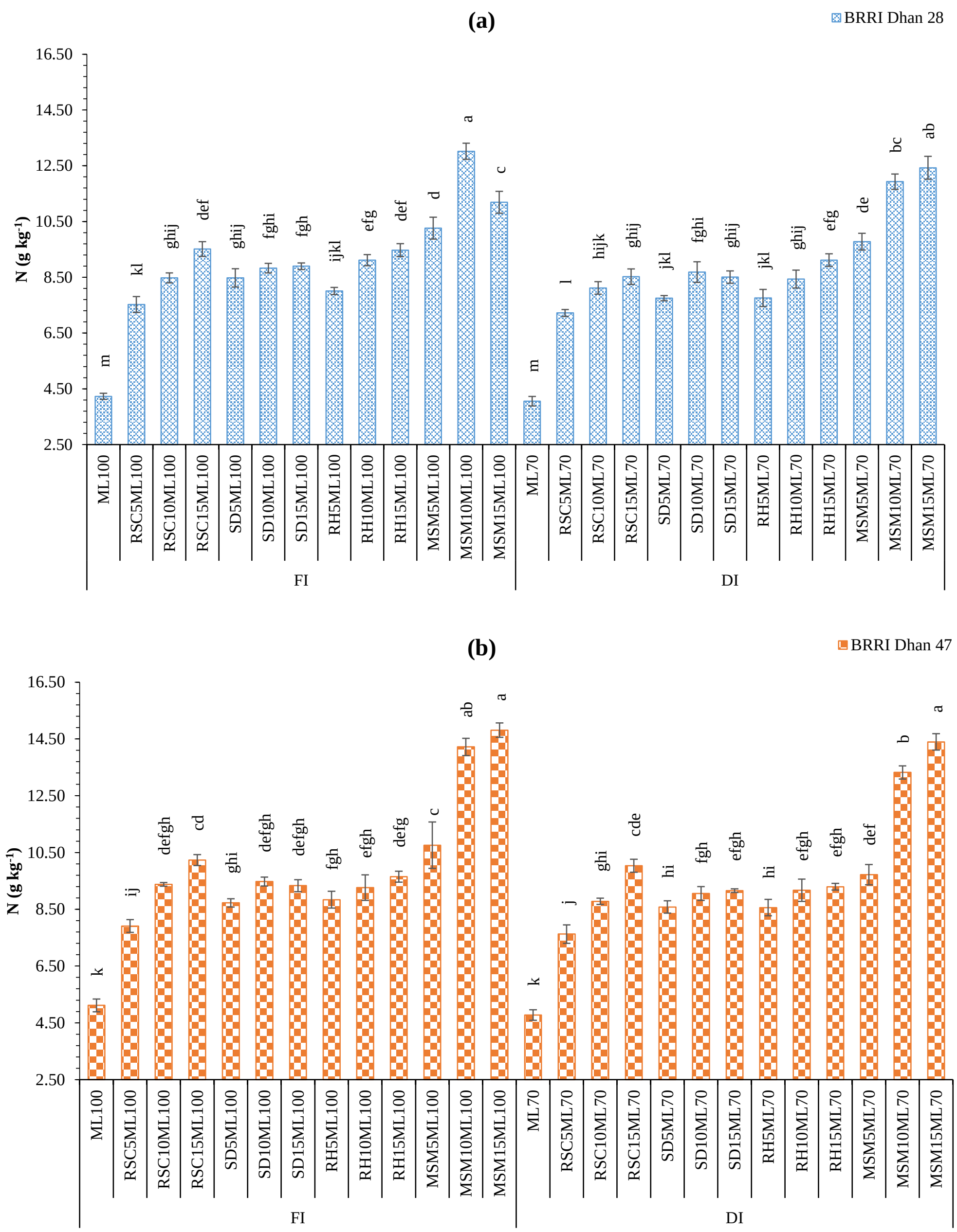


Figure 2. The N content in mature shoots of (a) BRRI Dhan 28 and (b) BRRI Dhan 47 as influenced by the treatments. The dissimilar letter-containing treatments are significantly different from each other ($p \leq 0.05$). FI, full irrigation; DI, deficit irrigation

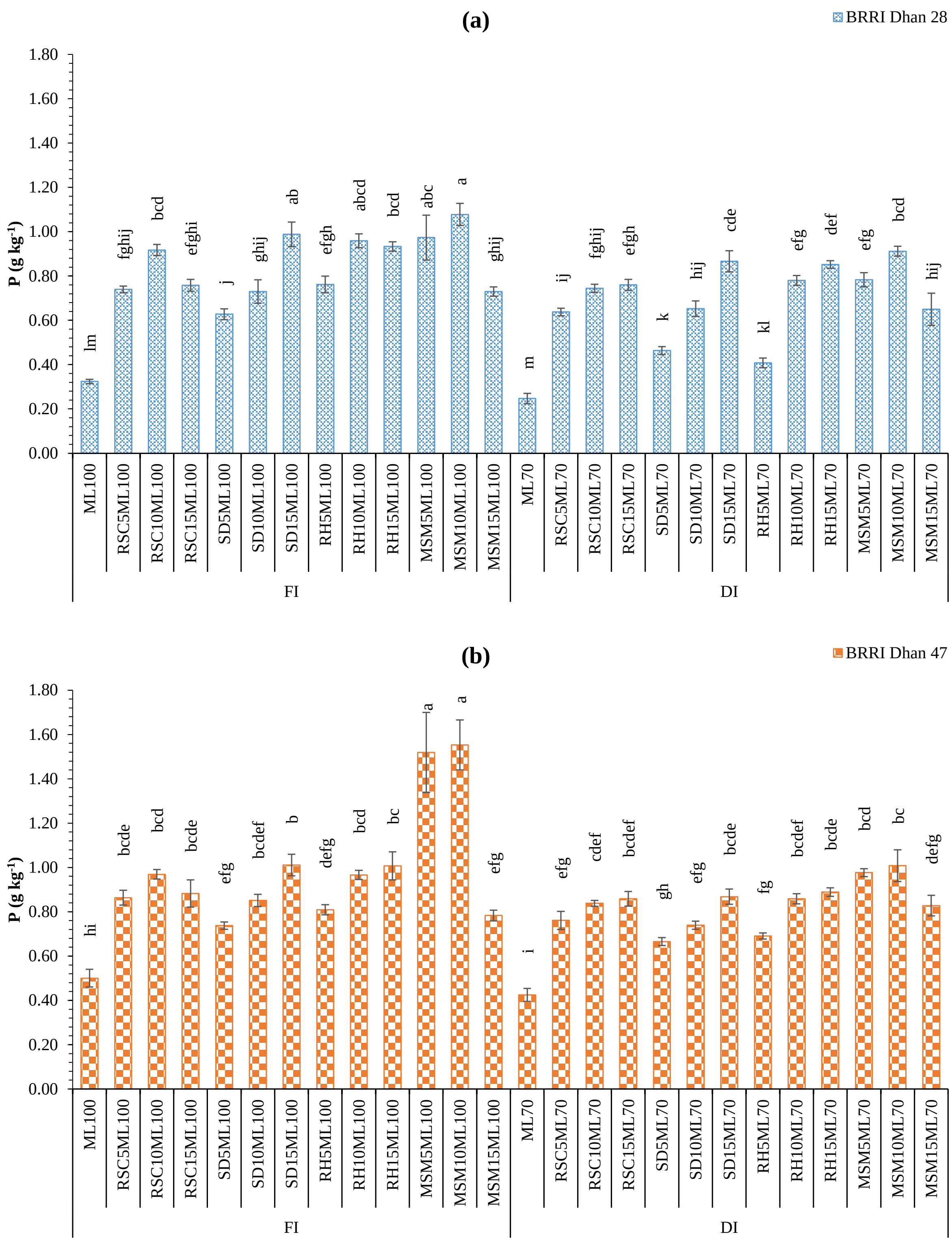


Figure 3. The P content in mature shoots of (a) BRRI Dhan 28 and (b) BRRI Dhan 47 as influenced by the treatments. The dissimilar letter-containing treatments are significantly different from each other ($p \leq 0.05$). FI, full irrigation; DI, deficit irrigation

Potassium (K^+) enrichment

Potassium content varied markedly with amendments and irrigations ($p < 0.001$) (**Table 3**). In BRRI Dhan 28, all amendments significantly ($p \leq 0.05$) increased K^+ content under both irrigation regimes (**Figure 4**). RSC at 10 t ha^{-1} under full irrigation recorded the highest K^+ content (19.03 g kg^{-1}), corresponding to a 438% improvement over deficit-irrigated controls (3.54 g kg^{-1}). In BRRI Dhan 47, SD at 15 t ha^{-1} achieved the maximum K^+ content (22.83 g kg^{-1}), while RH at 15 t ha^{-1} also showed significant enhancement (18.67 g kg^{-1}). These findings emphasize the critical role of RSC, SD, and RH in enhancing K nutrition, which is vital for osmotic regulation under stress.

Sodium/Potassium (Na^+/K^+) balance

Organic amendments significantly ($p \leq 0.05$) enhanced ionic balance by lowering the Na^+/K^+ ratio under both irrigation regimes in salt-sensitive and salt-tolerant genotypes over controls (**Figure 5**). In BRRI Dhan 28, RSC at 10 t ha^{-1} under full irrigation reduced the Na^+/K^+ ratio to 0.07, an 88% decrease relative to unamended deficit-irrigated plants (0.61). Similarly, in BRRI Dhan 47, SD at 15 t ha^{-1} minimized the ratio to 0.06, while RH at 15 t ha^{-1} achieved comparable reductions (0.07). These results suggest crop residue amendments facilitate Na^+ exclusion and K^+ retention, enhancing plant resilience under salinity and drought.

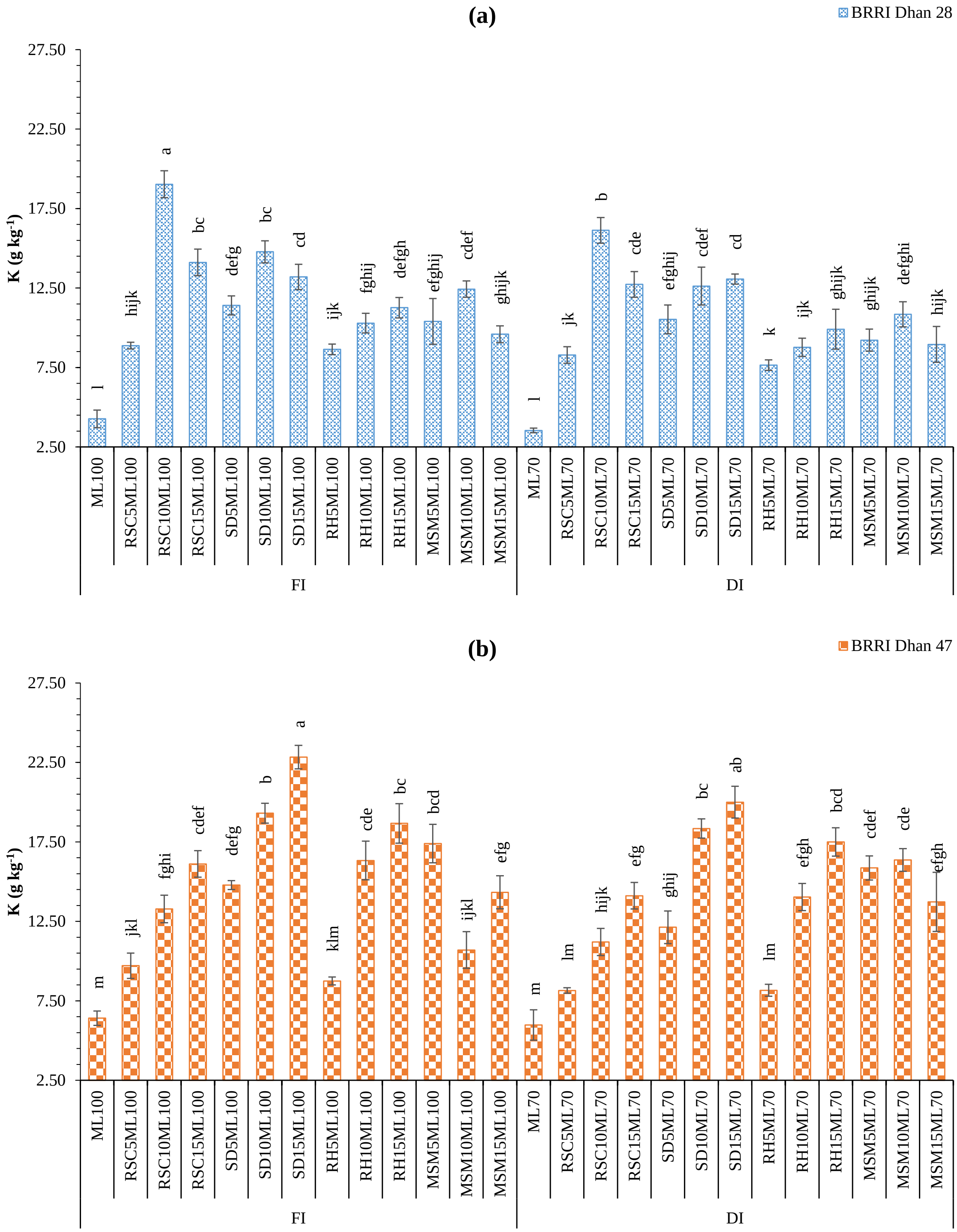
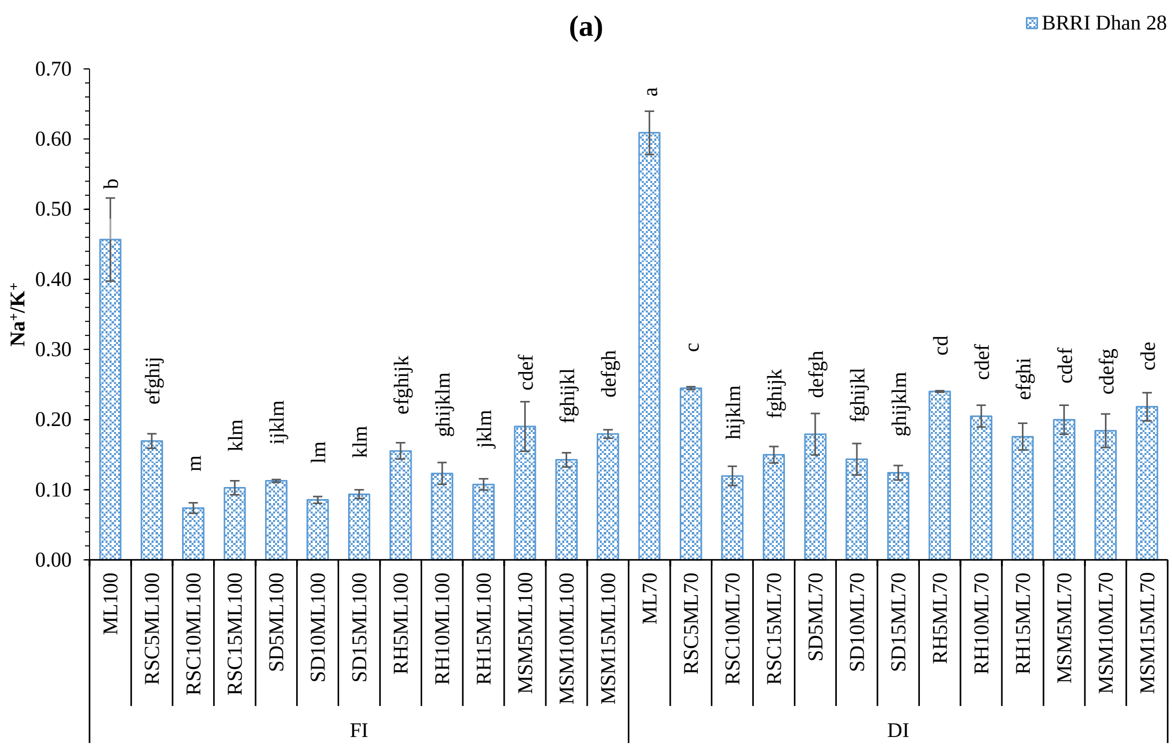


Figure 4. Changes in K content in rice straw of (a) BRRI Dhan 28 and (b) BRRI Dhan 47 as influenced by the amendments of the salt-affected soil in different irrigations. The dissimilar letter-containing treatments are significantly different from each other ($p \leq 0.05$). FI, full irrigation; DI, deficit irrigation



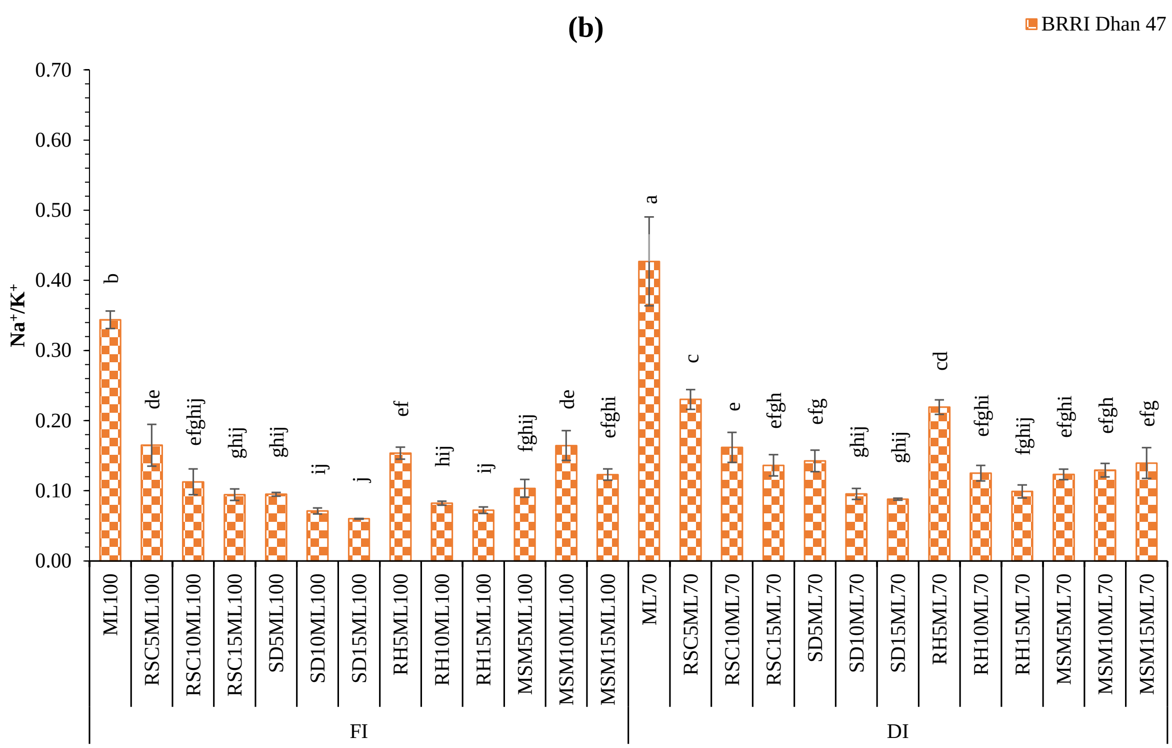


Figure 5. Changes in Na^+/K^+ ratio in rice straw of (a) BRRI Dhan 28 and (b) BRRI Dhan 47 as influenced by the amendments of the salt-affected soil in different irrigations. The dissimilar letter-containing treatments are significantly different from each other ($p \leq 0.05$). FI, full irrigation; DI, deficit irrigation

Table 3. General linear model analysis showing the effects of main factors (organic amendments and moisture levels) and their interactions on nutrient contents in the mature shoots of rice

	df	N	P	K	S	Ca	Mg	Fe	Mn	Zn	Na^+/K^+	N	P	K	S	Ca	Mg	Fe	Mn	Zn	Na^+/K^+
		BRRI Dhan 28										**BRRI Dhan 47**									
[a]OA	12	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
[b]ML	1	***	***	***	***	***	***	**	***	*	***	***	***	***	***	***	***	**	***	***	***
OA × ML	12	***	***	ns	***	ns	***	ns	ns	***	***	ns	***	***	***	ns	**	***	ns	ns	***

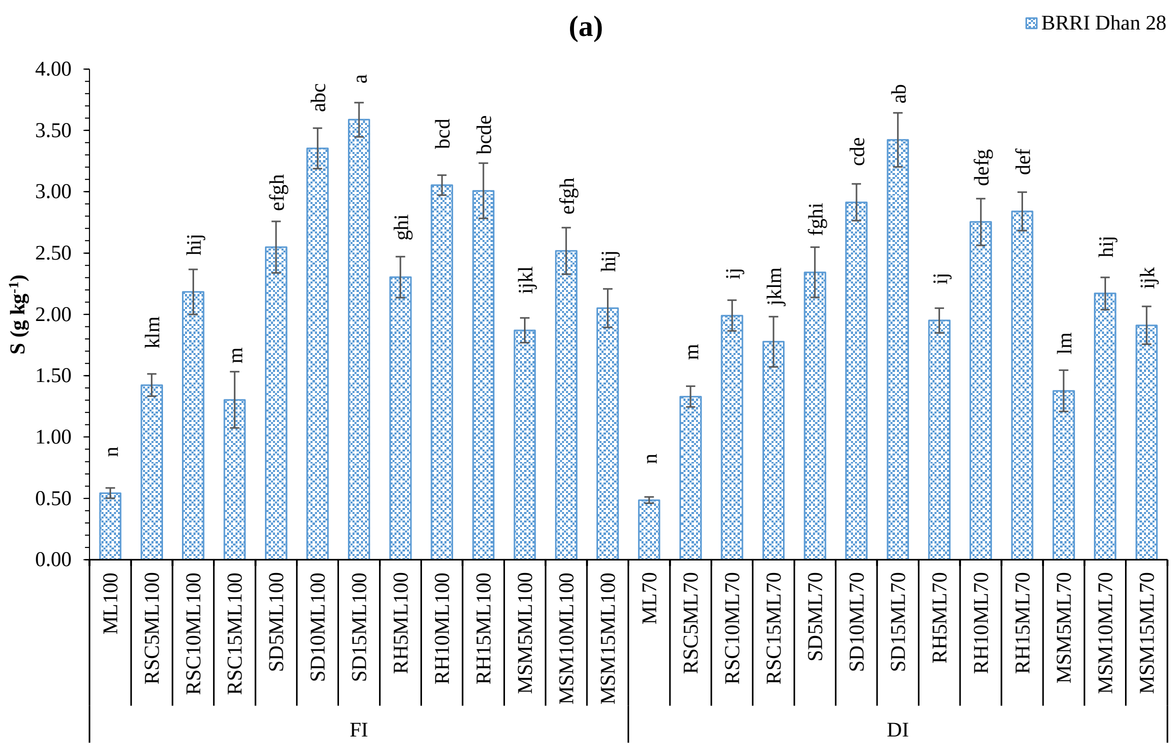
[a]Organic amendments, [b]Moisture levels. **Correlation is significant at the 0.01 level, *correlation is significant at the 0.05 level, [ns]correlation is not significant at the 0.05 level

Sulfur (S), Calcium (Ca), and Magnesium (Mg) content

The S content in BRRI Dhan 28 and BRRI Dhan 47 significantly ($p < 0.001$) responded to organic amendments, irrigation regimes, and their interaction (**Table 3**). All the amendments significantly ($p \leq 0.05$) increased S content in BRRI Dhan 28 compared to the controls under both irrigation practices (**Figure 6**). SD at 15 t ha^{-1} increased S content to 3.59 g kg^{-1} under full irrigation from 0.49 g kg^{-1} in unamended deficit-irrigated plots. RH at 15 t ha^{-1} similarly boosted S accumulation in BRRI Dhan 47 (3.50 g kg^{-1}), followed by SD at 15 t ha^{-1} (3.45 g kg ^{1}) under full irrigation.

MSM markedly improved Ca accumulation in both genotypes, especially in BRRI Dhan 47. MSM at 15 t ha^{-1} under full irrigation increased Ca content to 5.12 g kg^{-1}, compared to unamended dual-stressed plots (1.55 g kg^{-1}). In BRRI Dhan 28, MSM at 10 t ha^{-1} reached 4.02 g kg^{-1}, a notable improvement over the unamended controls. SD and RH also contributed positively, showing intermediate Ca levels between 3.1 and 3.6 g kg^{-1} across irrigation regimes (**Figure 7**).

Similarly, MSM was the most effective for Mg accumulation, especially under deficit irrigation. In BRRI Dhan 47, MSM at 15 t ha^{-1} raised Mg content to 4.41 g kg^{-1}, 142% higher than unamended dual-stressed plots (1.83 g kg^{-1}). In BRRI Dhan 28, MSM at 15 t ha^{-1} recorded Mg content of 4.3 g kg^{-1}, followed closely by RH (**Figure 8**). These results emphasize that MSM significantly enhances Ca and Mg nutrition in salt-sensitive and salt-tolerant rice genotypes under salinity and water deficit stress.



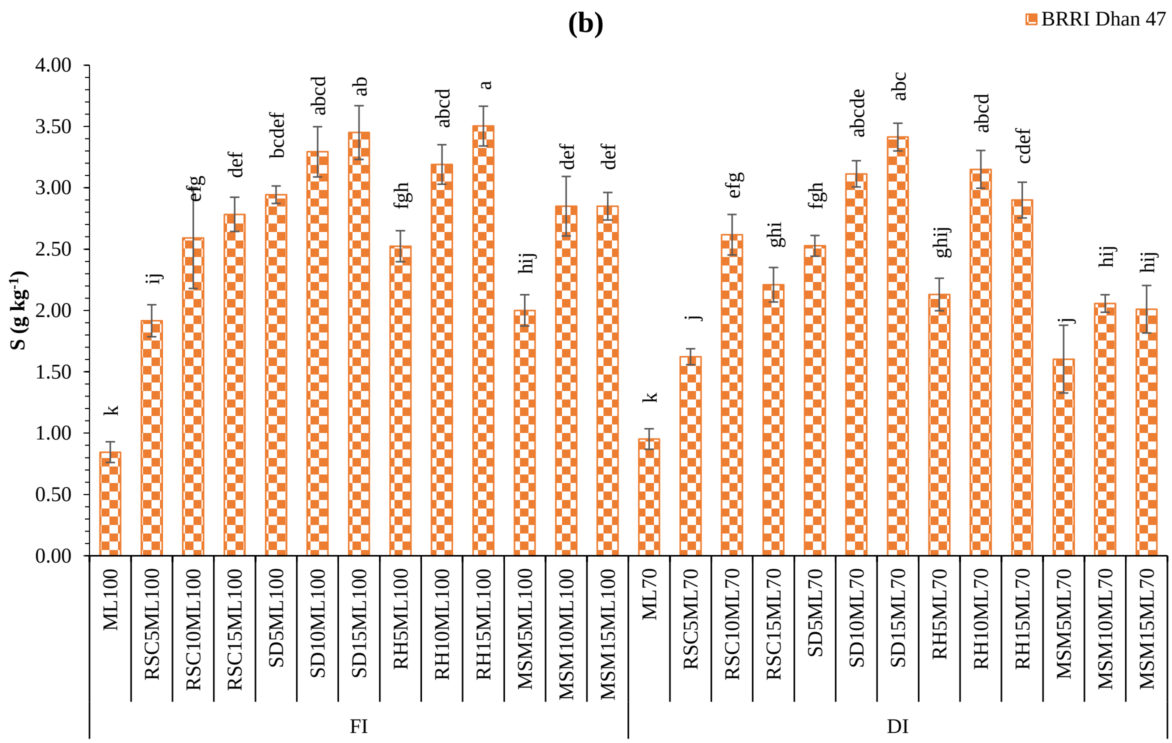
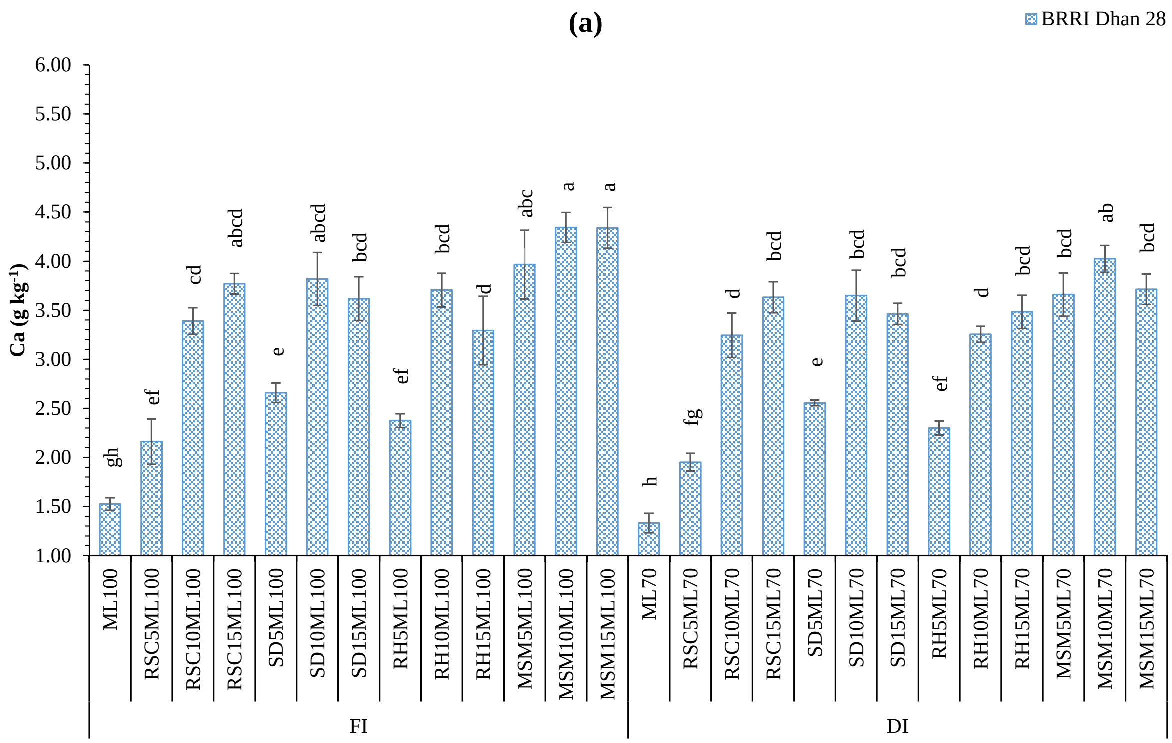


Figure 6. The S content in (a) BRRI Dhan 28 and (b) BRRI Dhan 47 due to amendments made in the salt-affected soil in varying irrigation practices. The dissimilar letter-containing treatments are significantly different from each other ($p \leq 0.05$). FI, full irrigation; DI, deficit irrigation



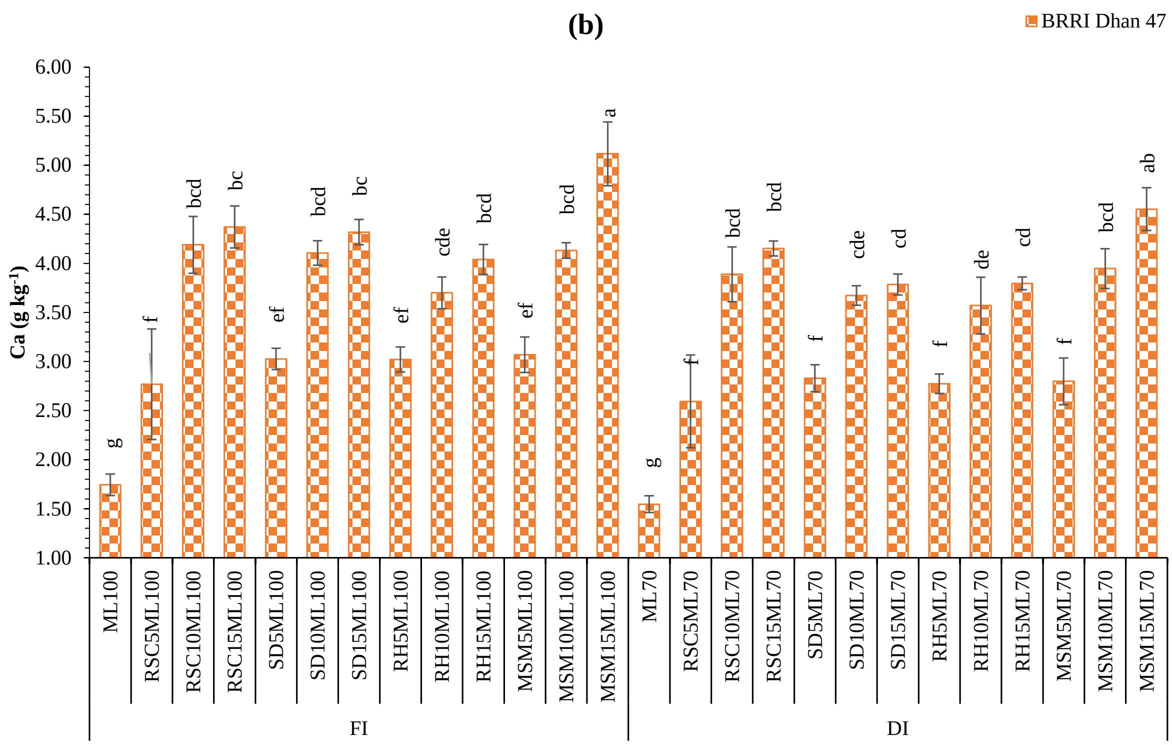
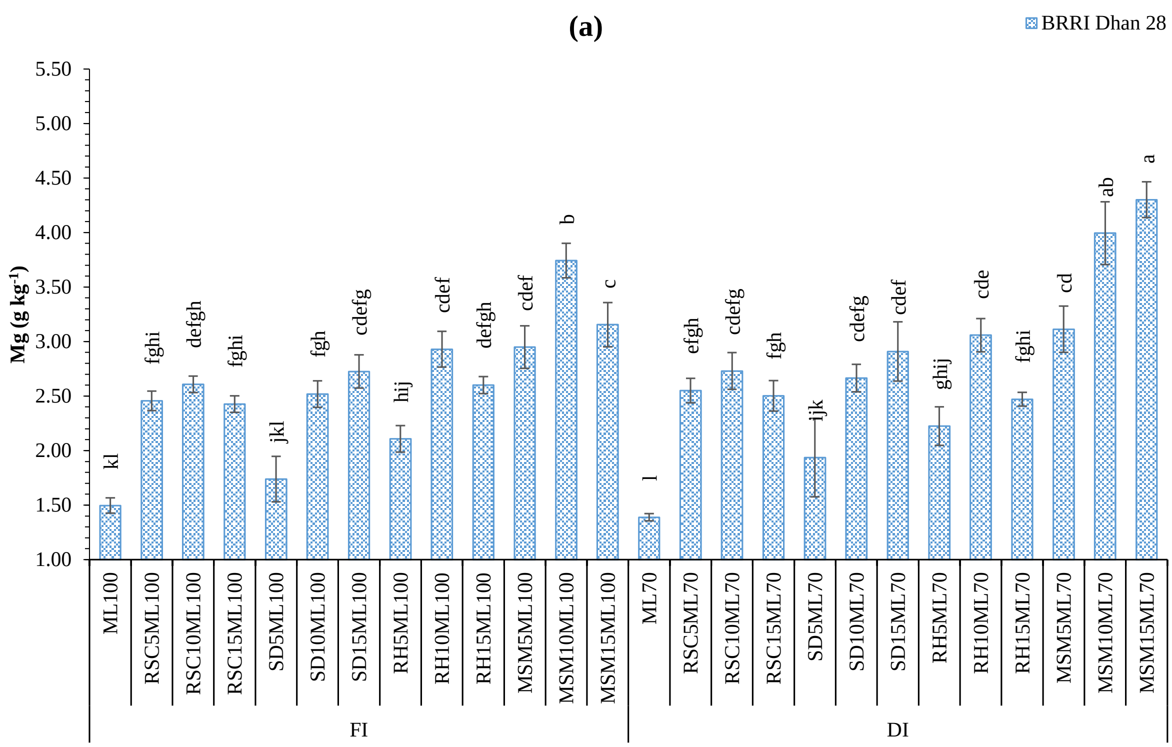


Figure 7. The Ca content in (a) BRRI Dhan 28 and (b) BRRI Dhan 47 due to amendments made in the salt-affected soil in varying irrigation practices. The dissimilar letter-containing treatments are significantly different from each other ($p \leq 0.05$). FI, full irrigation; DI, deficit irrigation



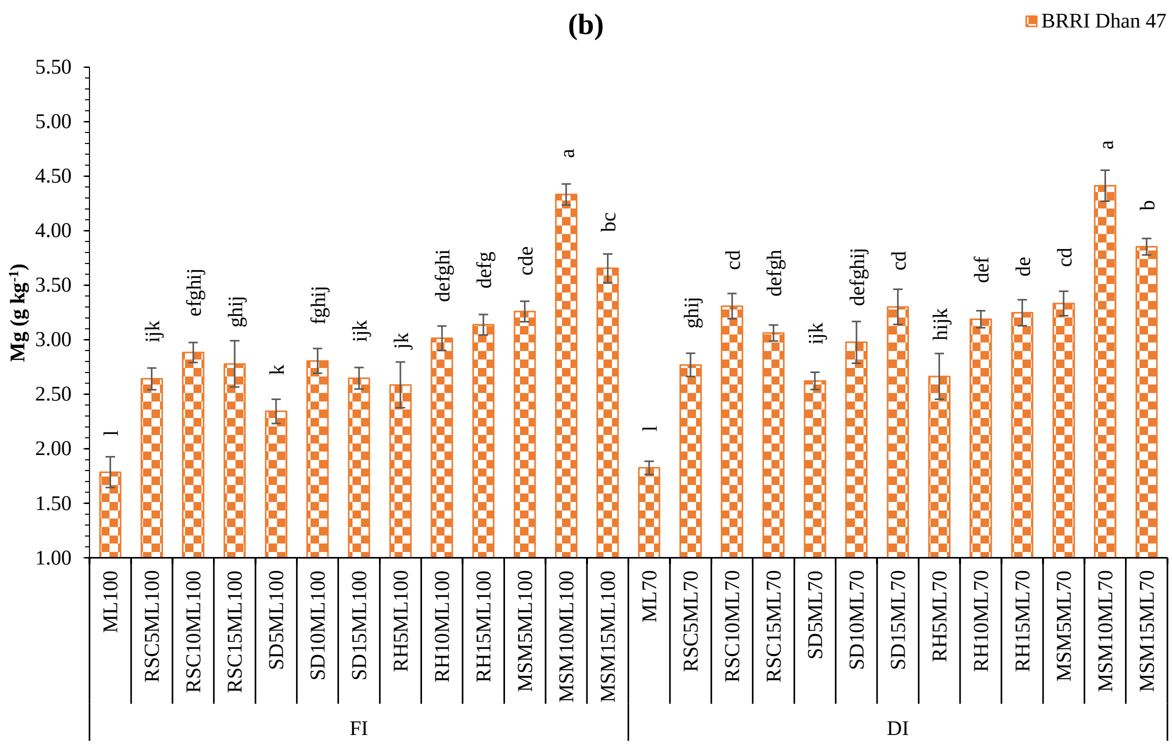


Figure 8. Changes in Mg content in the shoots of (a) BRRI Dhan 28 and (b) BRRI Dhan 47 at maturity due to the effect of the treatments. The dissimilar letter-containing treatments are significantly different from each other ($p \leq 0.05$). FI, full irrigation; DI, deficit irrigation

Micronutrient (Fe, Mn, Zn) content

Organic amendments significantly affect micronutrient accumulation in both genotypes across irrigation regimes (**Table 3**). In BRRI Dhan 47, RH at 15 t ha⁻¹ under full irrigation recorded the highest Fe content (0.45 g kg⁻¹), 156% higher than unamended deficit-irrigated plots (0.18 g kg⁻¹). In BRRI Dhan 28, MSM at 10 t ha⁻¹ under full irrigation achieved a notable Fe concentration (0.33 g kg⁻¹), outperforming other treatments (**Table 4**).

RSC at 15 t ha⁻¹ in BRRI Dhan 28 led to the highest Mn accumulation (36.29 mg kg⁻¹), a 205% increase compared to unamended dual-stressed plots (11.93 mg kg⁻¹). In BRRI Dhan 47, MSM at 10 t ha⁻¹ under full irrigation yielded the maximum Mn content (35.00 mg kg⁻¹).

Zn uptake was highly responsive to both genotype and amendment type. In BRRI Dhan 28, RH at 5 t ha⁻¹ under full irrigation resulted in the highest Zn content (20.67 mg kg⁻¹). In contrast, BRRI Dhan 47 achieved superior Zn accumulation under SD at 10 t ha⁻¹ (29.43 mg kg⁻¹) in deficit irrigation, a 227% improvement over the salt- and water deficit stressed controls (9.0 mg kg⁻¹).

Table 4. The micronutrients (Fe, Mn, and Zn) accumulated in rice straws of the two varieties as influenced by the amendments under varying irrigation practices

Treatment	Fe (g/kg)		Mn (mg/kg)		Zn (mg/kg)	
	BRRI Dhan 28	BRRI Dhan 47	BRRI Dhan 28	BRRI Dhan 47	BRRI Dhan 28	BRRI Dhan 47
ML100	0.15 lm	0.19 kl	12.98 mn	17.46 hi	6.17 k	8.43 m
RSC_5ML_{100}	0.21 fghijk	0.25 ijk	26.58 efg	27.63 cde	11.37 fgh	15.53 hijk
$RSC_{10}ML_{100}$	0.18 klm	0.38 bcd	28.37 def	25.96 efg	13.87 def	23.32 bc
$RSC_{15}ML_{100}$	0.25 defghi	0.28 fghij	36.29 a	26.53 def	15.65 cde	18.88 defg
SD_5ML_{100}	0.24 efghij	0.31 efgh	17.62 kl	26.63 def	9.67 hij	13.27 jk
$SD_{10}ML_{100}$	0.27 bcdef	0.25 hijk	21.58 ij	30.69 abcd	13.15 efg	28.37 a
$SD_{15}ML_{100}$	0.31 abc	0.35 cde	31.89 bcd	27.59 cde	10.50 ghi	16.27 ghij
RH_5ML_{100}	0.30 abcde	0.32 defg	25.79 fgh	24.40 efg	20.67 a	23.03 bc
$RH_{10}ML_{100}$	0.19 ijkl	0.40 abc	23.80 ghij	28.23 bcde	14.31 cdef	16.17 ghij
$RH_{15}ML_{100}$	0.19 jkl	0.45 a	35.24 ab	32.00 ab	10.51 ghi	13.72 jk

MSM_5ML_{100}	0.27 bcdef	0.31 efghi	16.65 l	24.37 efg	7.17 jk	10.17 lm
$MSM_{10}ML_{100}$	0.33 a	0.38 bcd	24.37 ghi	35.00 a	20.17 a	21.03 cd
$MSM_{15}ML_{100}$	0.21 fghijk	0.28 fghij	17.30 kl	17.67 hi	16.85 bcd	17.11 fghi
ML_{70}	0.13 m	0.18 l	11.93 n	15.70 i	8.23 ijk	9.00 m
RSC_5ML_{70}	0.21 ghijk	0.22 jkl	24.27 ghi	24.67 efg	11.79 fgh	16.23 ghij
$RSC_{10}ML_{70}$	0.20 hijkl	0.37 bcde	26.27 efgh	25.60 efg	14.34 cdef	24.30 b
$RSC_{15}ML_{70}$	0.23 fghij	0.33 cdef	32.87 abc	24.42 efg	16.32 bcd	19.40 def
SD_5ML_{70}	0.19 ijkl	0.27 ghij	17.90 kl	24.40 efg	11.39 fgh	14.17 ijk
$SD_{10}ML_{70}$	0.25 defghi	0.24 jkl	20.43 jk	28.23 bcde	12.63 efgh	29.43 a
$SD_{15}ML_{70}$	0.30 abcd	0.33 defg	29.48 cde	24.90 efg	12.02 fgh	17.33 fgh
RH_5ML_{70}	0.26 cdefg	0.28 fghij	26.17 efgh	22.50 fg	15.26 cde	24.53 b
$RH_{10}ML_{70}$	0.20 hijkl	0.35 cde	22.91 hij	26.03 ef	17.02 bc	17.07 fghi
$RH_{15}ML_{70}$	0.19 jkl	0.43 ab	31.89 bcd	30.70 abcd	15.41 cde	14.12 ijk
MSM_5ML_{70}	0.25 cdefgh	0.27 fghij	15.77 lm	21.63 gh	7.99 ijk	12.79 kl
$MSM_{10}ML_{70}$	0.32 ab	0.35 cde	23.13 ghij	31.47 abc	19.15 ab	20.67 cde
$MSM_{15}ML_{70}$	0.22 fghijk	0.33 defg	15.32 lmn	17.90 hi	16.57 bcd	17.59 efgh

The dissimilar letter-containing treatments are significantly different from each other ($p \leq 0.05$)

Relationship between nutrient content and Na^+/K^+ balance in the rice shoot

The correlation analysis for BRRI Dhan 28 showed several statistically significant relationships among nutrients (**Table 5**). Nitrogen was highly and positively correlated with Ca (r = 0.85**) and Mg (r = 0.85**). Phosphorus also had strong positive correlations with N (r = 0.68**) and Ca (r = 0.74**). Potassium showed moderate positive correlations with P (r = 0.58**) and S (r = 0.51**). Among micronutrients, Fe was significantly correlated with N, P, and S, while Zn showed positive correlations with most nutrients, including Mg (r = 0.49**) and Fe (r = 0.37**). Manganese had weaker correlations, significant only with P, K, and S. The Na^+/K^+ ratio showed significant negative correlations with all nutrients, especially K (r = -0.81**) and P (r = -0.71**).

In BRRI Dhan 47, similar patterns were observed (**Table 5**). Nitrogen showed strong positive correlations with Ca (r = 0.76**) and Mg (r = 0.86**). Phosphorus correlated with Mg (r = 0.63**) and Ca (r = 0.42**). Potassium was significantly correlated with S (r = 0.70**), Ca (r = 0.60**), and Mg (r = 0.35**). Micronutrients such as Fe and Mn were significantly correlated with most macronutrients, while Zn was positively correlated with Mn (r = 0.37**). Again, the Na^+/K^+ ratio was strongly negatively correlated with K (r = -0.83**), S (r = -0.79**), and several other nutrients.

Table 5. Pearson's correlation matrix of nutrient content and Na^+/K^+ ratio in mature rice shoot tissues

	N	P	K	S	Ca	Mg	Fe	Mn	Zn	Na^+/K^+
					BRRI Dhan 28					
N	1									
P	.68**	1								
K	.39**	.58**	1							
S	.40**	.57**	.51**	1						
Ca	.85**	.74**	.58**	.52**	1					
Mg	.85**	.60**	.26*	.27*	.72**	1				
Fe	.56**	.50**	.30**	.45**	.48**	.42**	1			
Mn	.16^{ns}	.51**	.52**	.40**	.26*	0.06^{ns}	.23*	1		
Zn	.54**	.33**	.24*	.25*	.40**	.49**	.37**	.34**	1	
Na^+/K^+	-.58**	-.71**	-.81**	-.69**	-.65**	-.38**	-.48**	-.58**	-.36**	1
					BRRI Dhan 47					
N	1									
P	.56**	1								
K	.36**	.39**	1							

S	.33**	.32**	.70**	1						
Ca	.76**	.42**	.60**	.67**	1					
Mg	.86**	.63**	.35**	.29**	.64**	1				
Fe	.43**	.52**	.45**	.59**	.56**	.52**	1			
Mn	.23*	.55**	.45**	.60**	.37**	.40**	.56**	1		
Zn	.27*	0.06ns	0.15ns	.41**	.45**	.29*	0.11ns	.37**	1	
Na^+/K^+	-.51**	-.50**	-.83**	-.79**	-.71**	-.46**	-.58**	-.57**	-.35**	1

**Correlation is significant at the 0.01 level, *correlation is significant at the 0.05 level, nscorrelation is not significant at the 0.05 level

Discussion

This study demonstrates that organic amendments from crop residues substantially improve rice nutrient status and ionic regulation under combined salinity and water deficit conditions. The pronounced ameliorative effects observed across both the salt-sensitive (BRRI Dhan 28) and salt-tolerant (BRRI Dhan 47) genotypes underscore the critical role of organic amendments in supporting rice resilience in salt-affected coastal agroecosystems.

Among the tested amendments, MSM consistently outperformed others in enhancing N, Ca, and Mg accumulation, regardless of irrigation regime or genotype. This efficacy is likely attributable to MSM's relatively low C/N ratio and lignin content, facilitating rapid mineralization and bioavailability of N, which aligns with prior findings in various crops (Litardo *et al.*, 2022; Rice *et al.*, 2007; Snyder *et al.*, 2009; Sultana *et al.*, 2021). Improved N nutrition under the MSM amendment may reduce salt and drought-related physiological stresses on nitrogen metabolism, resulting in better growth, biomass, and grain production (Sikder and Khan, 2024). Meanwhile, elevated Ca and Mg levels indicate MSM's ability to regulate ionic balance, water use efficiency, and photosynthetic function in stressful environments (Cha-um *et al.*, 2011; Chen *et al.*, 2017). Amendments under full irrigation conditions led to higher P accumulation than reduced water input, indicating an interaction between water management and nutrient uptake. This may be due to the synergistic effects of pH optimization through amendment decomposition, organic phosphate mineralization, and submergence conditions that collectively improve plant-available P (Amadou *et al.*, 2022; Jiang *et al.*, 2021). These mechanisms facilitate greater P uptake, improving plant nutritional status (Novair *et al.*, 2024; Phuong *et al.*, 2020).

RSC and SD markedly enhanced K^+ and S uptake, which is essential for plants' osmotic regulation and stress relief. The notable rise in K^+ accumulation caused by these amendments emphasizes their role in favoring selective K^+ absorption over Na^+, helping to maintain the crucial Na^+/K^+ balance (Fuchs *et al.*, 2005; Wang *et al.*, 2013; Zhao *et al.*, 2020). The reduction of the Na^+/K^+ ratio by up to 88% demonstrated here illustrates an effective ionic exclusion strategy that protects cellular functions against salt-induced ion toxicity and osmotic imbalance, which is regarded as one of the main mechanisms of salt tolerance (Basu *et al.*, 2021; Hussain *et al.*, 2021; Liu *et al.*, 2024; Sackey *et al.*, 2025). Enhanced S assimilation, particularly under SD and RH amendments, may promote the synthesis of reduced sulfur compounds like cysteine, glutathione, and reactive sulfur species, thereby reinforcing the antioxidative defense against salt-induced oxidative stress (Mangal *et al.*, 2022; Nazar *et al.*, 2011).

The distinct genotype responses observed further validate the intrinsic variability in salt tolerance mechanisms between BRRI Dhan 28 and BRRI Dhan 47. While the salt-tolerant BRRI Dhan 47 inherently maintains lower Na^+ and higher K^+ levels, showing inherent resilience, the salt-sensitive BRRI Dhan 28 exhibited a more pronounced nutrient uptake response to organic amendments, emphasizing the potential of tailored amendment strategies to rescue susceptible genotypes under abiotic stress.

Organic amendments significantly increased micronutrient uptake, including Fe, Mn, and Zn, which has implications for enhancing enzymatic activities, chlorophyll synthesis, and antioxidative capacity. (Kobayashi *et al.*, 2019). Particularly, Mn's role in mitigating salt stress via regulation of ion homeostasis and activation of antioxidant enzymes corroborates the benefits of organic inputs for micronutrient nutrition under salinity (Rahman *et al.*, 2016). The increase in Zn content, especially in the salt-tolerant genotype under deficit irrigation, is notable given zinc's recognized function in alleviating salt-induced oxidative damage and hormonal balance (Nadeem *et al.*, 2020; Shao *et al.*, 2023).

The strong positive correlations among major macronutrients (N, P, K, Ca, Mg, S) and their significant negative relationships with the Na^+/K^+ ratio across both genotypes reaffirm the interdependence of nutrient uptake and ion homeostasis in conferring salt and drought tolerance. These synergistic nutrient interactions facilitate improved metabolic efficiency, photosynthesis, and osmotic adjustment, collectively enhancing plant growth under abiotic stresses (Awad *et al.*, 1990; Hafez *et al.*, 2021; Kamal *et al.*, 2024; Khan, Siddique, *et al.*, 2023; Khan, Mahmood, *et al.*, 2023; Li *et al.*, 2025; Mangal *et al.*, 2022; Mostofa *et al.*, 2022). Moreover, the enhanced nutrient uptake likely mediates the physiological strength required to withstand combined stresses more effectively than single stress amelioration. The consistent and significant negative correlations between Na^+/K^+ and most essential nutrients highlight that rice's main salt-tolerance mechanisms are improved Na^+ exclusion and better nutrient uptake (Ali *et al.*, 2024; Basu *et al.*, 2021; Hussain *et al.*, 2021).

Organic amendments have received much attention for improving salt-affected soils by enhancing their physical, chemical, and biological properties (Elmeknassi *et al.*, 2024; Leogrande and Vitti, 2019; Meena *et al.*, 2019). These amendments provide essential macro- and micro-nutrients, increase water holding capacity, enhance microbial and enzyme activities, improve soil fertility, and support plant growth (Che *et al.*, 2023; Gunarathne *et al.*, 2020; Oo *et al.*, 2015; Tejada *et al.*, 2006; Wu *et al.*, 2018; Yang *et al.*, 2018). They positively affect soil structure, including bulk density, porosity, and hydraulic conductivity, which helps leach excess salts from the root zone and decreases soil pH, EC, SAR, and ESP (Ding *et* *al.*, 2020; Phuong *et al.*, 2020; Prapagar *et al.*, 2012). Additionally, organic amendments increase nutrient availability and plant uptake, water use efficiency, helping maintain nutrient balance and ion homeostasis (El-Katony *et al.*, 2021; Haque *et al.*, 2021; Ramteke *et al.*, 2022; Xiao *et al.*, 2025; Zhao *et al.*, 2020). The synergy between enhanced soil health and plant nutrient homeostasis represents a sustainable pathway to mitigate salinity and water deficit constraints.

This study highlights the crucial role of crop residue-based organic amendments in reducing the combined effects of salt and water deficit stress on rice nutrient dynamics and ion homeostasis. The diverse effects of amendments underscore the importance of using a varied mix to tailor nutrient management strategies based on genotype sensitivity and environmental conditions. These insights offer valuable guidance for sustainable soil and crop management practices that enhance productivity, resilience, and food security in salt-affected coastal areas amid changing climate conditions.

Conclusion

This study demonstrates that incorporating crop residue-based organic amendments significantly alleviates the combined effects of salt and water deficit stress in rice cultivated on salt-affected coastal soils. Among the amendments, mustard seed meal (MSM) proved most effective in enhancing N, Ca, and Mg uptake, while rice straw compost (RSC) and sawdust (SD) notably improved K^{+} and S assimilation. These amendments also substantially reduced the Na^{+}/K^{+} ratio, maintaining ionic homeostasis under saline and moisture-stressed conditions. Improved nutrient acquisition of N, P, K, Ca, Mg, and essential micronutrients suggests that organic amendments enhance plant resilience by optimising physiological and biochemical functions necessary for sustaining growth and productivity. Furthermore, significant positive correlations among macronutrients and micronutrients, along with strong negative associations between Na^{+}/K^{+} ratios and nutrient uptake, underscore the role of organic amendments in enhancing ion regulation mechanisms. These findings support using locally available crop residues as a cost-effective and eco-friendly approach to restore soil quality, promote nutrient cycling, and reduce the negative impacts of salinity and drought. Incorporating such amendments into coastal agroecosystems can be a sustainable solution to enhance rice productivity, improve stress tolerance, and secure food security under changing climatic conditions.

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