Silicon Supplementation Boosts Salt Resilience of Traditional Rice Varieties by Ionic Regulation and Nutrient Balance

Umme Kulsum Shanta*, Mohammad Asadul Haque, Samsunnahar Pranto, Saimon Islam, Partho Sarker Dhrubo, Montaha Mostafa Soha, Fatema Nasrin Lamia, Md Kamal Hossain and Md Fazlul Hoque

Department of Soil Science, Patuakhali Science and Technology University, Dumki, Patuakhali-8602, Bangladesh

*Correspondence: shanta.pstu.ag@gmail.com
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Abstract: Salinity is the most important abiotic constraint affecting rice production in coastal zones globally, due to the low inherent salt tolerance of rice. Silicon (Si) has been reported as an effective element in improving salinity tolerance, but nothing is known about its tolerance with the conventional coastal rice genotypes. For this experiment, three old rice cultivars – Sadamota, Kalokhoia and Sakkorkhana were tested in saline-control (1.72 dS m-1) and saline (6 dS m-1) environments to evaluate the possibility of enhancing their salt tolerance by Si supplementation. The soil was subjected to a factorial pot trial with two levels of Si (0 and 100 mg Si kg-1 soil). Salinity caused a significant decrease in plant height (11.3%), number of tillers per hill (11.5%), root volume (29.3%), root dry weight (25.1%) and shoot dry weight (21.9%) compared to the saline-control, and caused a significant increase in Na+ concentration in plant cells and thus disturbed the ionic balance. In contrast, silicon application was successful in minimizing these adverse impacts through its effects on morpho-physiological traits and ion homeostasis. The Si application rate of 100mg Si kg-1 soil led to the increase in plant height of 4.5%, tillers hill-1 by 6.9%, root volume by 14.5%, root dry weight by 32.2%, and shoot dry weight by 8.6% when compared with the control (Si). The silicon application significantly increased total Si uptake by 27.6%, and decreased both Na+ content in shoot by 12.8% and Na+: K+ ratio in shoot by 15.3%. The root development and Si uptake of Kalokhoia was the best among the various types, as was its salt resistance, suggesting genotype-specific responses to Si supplementation. The results show that applying 100 mg kg-1 of Si to the soil greatly lessens the negative effects of salinity by enhancing the morpho-physiological characteristics, ionic control, and nutrient balance of traditional monsoon rice.

Keywords: Calcium silicate, coastal region, Na^+: K^+ ratio, soil salinity, traditional rice

Introduction

Salinity is recognized as one of the most important environmental stresses that affects the productivity of agriculture in coastal regions worldwide, particularly in low-lying deltaic countries such as Bangladesh (Sikder et al. 2016, Shila et al. 2016, Kumar et al. 2018; Haque and Hoque 2023). More than 1.16 million hectares (1/4 of the total 2.85 million) of coastal land in Bangladesh is affected by salinity, up 40% from 1973. Sea level rise, decreased freshwater flow upstream, and unpredictable weather patterns brought on by climate change are the main causes of this increase (Jodder et al. 2016). Salinity is a serious problem affecting the crop productivity in Bangladesh coastal region and other parts of the globe, especially rice (Haque et al. 2026). In Bangladesh, Oryza sativa L (rice) is regarded as the main staple food crop for most of the people. Bangladesh is the third largest producer of paddy rice in the world, producing 55 million tonnes of paddy rice on 10.5 million hectares of rice land, with an average yield of 3.25 t ha-1, and accounting for nearly 76% of the country's total cropped area (Pranto et al. 2023). Monsoon rice is the most extensive growing season for rice with numerous traditional varieties that are valued for their grain quality, flavour and ability to adapt to conditions (Haque et al. 2025a). Planting rice during pre-monsoon (April-August) and winter (December-May) has been destroyed in many cases because of its high salt tolerance, and so farmers leave their fields fallow during the vulnerable months.

Salt stress exerts its negative effects primarily through osmotic stress, ion toxicity (excessive Na^+ and Cl^- accumulation), nutrient imbalance (notably K^+ deficiency), and oxidative damage caused by overproduction of reactive oxygen species (Khanam et al. 2020). These physiological disruptions result in decreased chlorophyll content, impaired photosynthesis, and cellular damage, eventually reducing yield and quality (Haque et al. 2023a, 2024a, 2025b). Therefore, developing effective, low-cost strategies to improve the salt resistance of traditional rice varieties are essential for maintaining sustainable food security in coastal zones.

Conventional approaches such as breeding and cultivation of salt tolerant varieties have provided some progress, but these varieties often exhibit undesirable agronomic traits or poor adaptability to local farming conditions. Moreover, farmers are dedicated to grow the traditional monsoon rice varieties due to their low input requirement, cultural familiarity, and stable performance in non-saline coastal ecosystem although their relatively low yield (2.0-3.0 t ha^{-1}). Consequently, alternative management practices that can strengthen the salt resilience of these traditional genotypes are urgently needed.

In this context, silicon (Si) has emerged as a beneficial element in mitigating abiotic stresses, including salinity, particularly in graminaceous crops like rice which actively accumulate Si in their tissues (Pranto et al. 2025, Sultana et al. 2021, Shanta et al. 2025). It also alleviates lipid peroxidation and stabilizes chlorophyll under stress conditions (Sume et al. 2023).

Previous work has shown that 100 mg Si kg^{-1} soil recorded significantly higher tiller production (9.7 $hill^{-1}$) and biomass yield (15.3 g pot^{-1}) of BRRI dhan73 rice variety under non-saline pot culture condition (Mobaswera et al. 2023). However, the potential of this Si rate to alleviate salinity stress in traditional rice remains unexplored. Hence, this study was undertaken to evaluate the morpho-physiological and biochemical responses of selected traditional monsoon rice varieties (*Sadamota*, *Kalokhoia*, and *Sakkorkhana*) to Si supplementation under controlled salinity levels. The outcomes of this research is expected to identify new perception for the function of Si in mitigating salt stress and supporting the development of Si-based agronomic practices for sustainable rice production in saline-prone coastal regions.

Materials and Methods

Experimental site

The study was performed using a pot culture experiment in the Department of Soil Science, Patuakhali Science and Technology University (PSTU) under Patuakhali district. Geographically, the site is positioned at 22.46465ºN latitude and 90.38843ºE longitude. The study area situated around 90 km inside the Bay of Bengal Sea, and is heavily affected by tidal water inundation specifically in monsoon. This location falls within the Ganges Tidal Floodplain under Agro- ecological Zone 13 (AEZ 13) of Bangladesh. During monsoon season of 2024 (August-November) the experiment was carried out.

Design and treatments

A completely randomized design (CRD) comprising three replications was followed in this three-factor pot experiment. Two silicon levels (Si_0 -control and Si_{100}-100 mg Si kg^{-1} soil) and two salinity level (Saline-control (1.72 dS m^{-1}) and 6 dS m^{-1} salinity) were applied to each of three selected popular traditional low yielding rice varieties commonly cultivated in the tidal floodplain areas of coastal Bangladesh: namely *Sadamota*, *Kalokhoia* and *Sakkorkhana*. The varieties are adaptable in many unfavorable conditions of the coastal ecosystem having average yield potential of approximately 2.0-3.0 ton ha^{-1}. In the experiment 0 and 100 mg Si kg^{-1} soil was used as the Si treatment, because in our earlier studies we have found that 100 mg Si kg^{-1} soil in pot culture condition and 80-100 kg Si ha^{-1} in field condition can make a significant difference in rice and other field crops (Mobaswera et al. 2023). Therefore, we have used the 100 mg Si kg^{-1} soil as the Si treatment. In the present experiment, we have used three traditional rice varieties (*Sadamota*, *Kalokhoia* and *Sakkorkhana*). All those varieties have no previous record of salt tolerance, but those varieties are very popular in coastal non-saline region of the country. We have assumed that 6 dS m^{-1} continuous salinity will significantly reduce the growth of those rice varieties. In addition, in that saline situation Si application may improve the salt tolerance capacity of those traditional rice varieties.

Soil collection, pot preparation and fertilizer application

In the first week of July 2024, top 15 cm depth soil was collected using a spade from a farmer's field vicinity of PSTU campus. The area was typically medium low-land, monsoon season rice is the dominating crop in the ecosystem. The collected soils were then mixed properly and spread on a clean surface for air-drying. Soil clods were broken with a wooden hammer when they were adequately dried.

The initial soil was chemically analyzed for different physicochemical parameters (Page et al. 1982). The soil that was used for the experiment was silty clay loam in texture having saturation paste extract electrical conductivity of 1.72 dS m^{-1} (non-saline) and pH of 5.6 (slightly acidic). The soil had 1.10 g kg^{-1} total N, 13.2 g kg^{-1} organic C, 5.2 mg kg^{-1} available P, 0.29 cmol kg^{-1} exchangeable K, and 31% total Si content. For this experiment, 36 plastic pots (2- liter capacity each) were used, with each pot filled with 1 kg of the processed soil. The soil was moistened with sufficient water to achieve a workable muddy texture before planting. Essential plant nutrients viz. N, P, K, S and Zn were added to soil at the rates of 120, 20, 100, 16 and 10 mg kg^{-1} soil, respectively through Urea, Triple Superphosphate (TSP), Muriate of Potash (MoP), Gypsum and Zinc sulfate, respectively. Urea was split into three equal doses and applied at 0, 25 and 50 days after transplanting. Application of silicon (Si) was made to 50% of the experimental pots (eighteen pots) using Calcium Silicate ($CaSiO_3$) during soil preparation. After two weeks, when the young seedlings were properly established, half of the pots were placed in water tank (length 120cm, breadth 100cm and height 30 cm) consisting 6 dS m^{-1} saline water developed through dissolving NaCl in water. Certain level of water height was maintained in the water tank so that 1 cm water height always remained above pot soil surface. The other 50% of the experimental pots was placed in another tank consisting fresh water. The same salt concentration was maintained up to the harvest of the plants. As the tested three traditional rice varieties have no previous record of salt tolerance; therefore this level of continuous salt stress could significantly hamper plant growth.

Seed sowing and intercultural operations

Uniform and healthy seeds of *Sadamota*, *Kalokhoia* and *Sakkorkhana* were presoaked under water for 24 hours and wrapped into a gunny bag. To get adequately sprouted seeds, all the seeds were kept in a warm place for four days. At first, eight healthy sprouted seeds of *Sadamota*, *Kalokhoia* and *Sakkorkhana* were planted in each plastic pot on 05 August 2024. Four healthy seedlings were kept per pot by uprooting extra seedlings at 14 days after planting. Watering was done when ever needed. Algae were removed by hands from water surface. Rice stem borer and green leafhoppers were successfully controlled by spraying insecticides (Virtako) in every 10-day intervals.

Harvesting

The plants were harvested on October 27, 2024, by cutting them off at the root. The roots were carefully removed from the soil after rinsing in clean water and the dry weight of the roots and shoots obtained after drying in the oven at 62°C for 48 hours.

Data recording

Plant height, tillers per pot, and the dry weight of the roots and shoots were among the plant metrics. After harvesting silicon, sodium and potassium concentration in the root and shoot was taken as well as root volume. A graduated cylinder was used to measure the root volume using the water displacement method. Water volume of the root was determined from the increase in water volume after submergence of roots. For silicon, sodium and potassium determinations, the root and shoot samples were coarsely chopped to a size less than 2 mm, oven dried and then thoroughly mixed. One gram of the material was put into a digestion tube for digestion. Plant samples were digested in a 5:2:1 ratio of nitric acid (HNO_3), perchloric acid ($HClO_4$) and sulphuric acid (H_2SO_4). The Si content of the prepared digested sample was ascertained using the procedure described by (Yoshida et al. 1976). Root and shoot production and specific Si content data were used to calculate the shoot and root Si assimilation. The chlorophyll content of the third fully expanded leaf was measured 40 days after sowing of the seeds, following the method described by (Coombs et al. 1985), after digestion and filtering of filtrates that were found.

Data analysis

Data collected from the chemical analysis and plant development were analysed statistically using data analysis STAR (Statistical Tool for Agricultural Research). A three-way analysis of variance (ANOVA) model was used to determine the effects of Si dose, rice cultivar, salinity level and their interactions on various plant parameters. The statistical analysis was done using Least Significance Difference (LSD) test at 5% level of significance. STAR software was used to obtain the Pearson's correlation coefficient.

Results

Effects of silicon, salinity and variety on growth parameters of rice

Plant height

Due to salinity, plant height of rice was reduced significantly having the highest mean plant height (117.4 cm) was recorded at saline-control condition (Table 1). But due to salinity, the mean plant height of rice reduced to 104.1 cm. Therefore, salinity decreased plant height by 11.3% over saline-control condition. By application of Si in soil, plant height of rice was significantly increased. Under Si_0 treatment the plant height was 108.3 cm (Table 1), which significantly increased to 113.2 cm at Si_{100} treatment, showing 4.52% over control. Considering varietal effect, the highest plant height was recorded in Sadamota (115.1 cm), which followed by Kalokhoia (113.8 cm) and Sakkorkhana (103.3 cm). Concerning the interaction effects Salinity:Silicon and Salinity:Variety interactions were significant. Considering Salinity:Silicon interaction, under both silicon control and 100 mg Si kg^{-1} soil applied condition; the salinity stress notably decreased the plant height of rice (Table 2). Again, under saline-control conditions, 100 mg Si kg^{-1} soil had higher plant height than the silicon control; but in saline conditions, Si control and the 100 mg Si kg^{-1} soil were statistically similar. The Salinity:Variety interaction has been shown in Table 2, which indicated that 6 dS m^{-1} salinity markedly lowered the plant height of all the tested rice varieties.

Table 1. Growth parameters of rice varieties as influenced by silicon application under different salinity levels

Factors	Plant height (cm)	Tillers $hill^{-1}$ (no.)	Root volume (cc)	Root dry wt. (g pot^{-1})	Shoot dry wt. (g pot^{-1})
Salinity					
Saline-control (Non-saline)	117.4	11.1	14.7	3.39	13.7
Saline (6 dS m^{-1})	104.1	9.8	10.4	2.54	10.7
Significance level	***	***	***	***	***
SE (±)	1.80	0.309	0.400	0.121	0.321
Silicon					
Si 0 mg kg^{-1} soil	108.3 b	10.1 b	11.7	2.55 b	11.7 b
Si 100 mg kg^{-1} soil	113.2 a	10.8 a	13.4	3.37 a	12.7 a
Significance level	*	*	***	***	**
SE (±)	1.80	0.309	0.400	0.121	0.321
Variety					
Sadamota	115.1 a	11.2 a	12.8 b	3.13 b	14.1 a
Kalokhoia	113.8 a	10.8 b	14.2 a	3.49 a	13.3
Sakkorkhana	103.3 b	9.4 c	10.7 c	2.27 c	9.2 b
Significance level	***	***	***	***	***
SE (±)	2.20	0.378	0.490	0.148	0.393
Significance level of interactions					
Salinity:Silicon (SE ±)	*(2.54)	ns(0.437)	***(0.567)	ns(0.171)	ns(0.0.454)
Salinity:Variety (SE ±)	*(3.11)	*(0.535)	**(0.693)	**(0.210)	**(0.556)

Silicon:Variety (SE ±)	ns(3.11)	ns(0.535)	**(0.693)	ns(0.210)	ns(0.556)
Salinity:Silicon:Variety (SE ±)	ns(4.40)	ns(0.757)	ns(0.981)	ns(0.297)	ns(0.786)
CV%	4.86	8.88	9.57	12.3	7.89

Note: *, **, *** and ns indicate significant at 5, 1, 0.1 % level, and not significant, respectively. CV- Coefficient of variation; SE- Standard error of means. Similar aesthetic small letters in a column for each single effect are not significantly different at 5% level of probability.

Table 2. Effects of Salinity: Silicon interactions, and Salinity: Variety interactions on plant height of rice

Factors	Plant height (cm)		
	Saline-control	Saline (6 dS m^{-1})	Difference
Salinity:Silicon interactions (n=9)			
Si0 (Control)	112	103	9*
Si100	122	104	18*
Difference	10*	1^{ns}	
Salinity:Variety interactions (n=6)			
Sadamota	119 ab	112 a	7*
Kalokhoia	121 a	107 a	14*
Sakkorkhana	113 b	94 b	19*

Similar small letters in a column are not significantly different.
^{ns}-Not significant, *-Significant at 5% probability level

Tillers per hill

The number of tillers hill^{-1} significantly responded with single effect of salinity. At saline-control condition the number of tillers hill^{-1} was 11.1 which decreased to 9.8 tillers hill^{-1} under saline condition (Table 1). Therefore, salinity reduced the number of tillers by 11.5%. Single effect of Si was also significantly influenced the number of tillers hill^{-1}. When Si was not applied, the mean number of tillers hill^{-1} was 10.1, which was increased to 10.8 tillers hill^{-1} at 100 mg Si kg^{-1} soil. Si application increased the number of tillers hill^{-1} by 6.93% over control. In case of single effect of variety, the highest tiller hill^{-1} was recorded (11.2 tillers hill^{-1}) in Sadamata, then in Kalokhoia (10.8 tillers hill^{-1}) and Sakkorkhana had the least (9.4 tillers hill^{-1}). The interaction effect between salinity and variety was significant at 5% level of significance. Based on the interaction effect, salinity treatment significantly reduced the tiller production in Sadamota, which was insignificant in Kalokhoia and Sakkorkhana (Table 3). Again, under saline-control condition the grade of producing tiller hill^{-1} was Sadamata > Kalokhoia > Sakkorkhana. Interestingly under saline condition this grade was Sadamata = Kalokhoia > Sakkorkhana (Table 3).

Table 3. Effects of salinity:variety interactions on different growth parameters of rice

Plant parameters	Salinity:Variety interactions		
	Saline-control	Saline (6 dS m^{-1})	Difference
Number of tillers hill^{-1}			
Sadamota	12.5 a	9.8 ab	2.7*
Kalokhoia	11 b	10.5 a	0.5^{ns}
Sakkorkhana	9.8 c	9 b	0.8^{ns}
Root volume of rice (cc)			
Sadamota	15.1 b	10.5 ab	4.6*
Kalokhoia	17.1 a	11.1 a	6.0*
Sakkorkhana	11.6 c	9.6 b	2.0*

Root dry wt. (g pot^{-1})			
Sadamota	3.65 b	2.60 a	1.05*
Kalokhoia	4.09 a	2.88 a	1.21*
Sakkorkhana	2.40 c	2.14 b	0.26^{ns}
Shoot dry wt. (g pot^{-1})			
Sadamota	16.3 a	11.8 a	4.5*
Kalokhoia	14.5 b	12.1 a	2.4*
Sakkorkhana	10.1 c	8.2 b	1.9*

Similar small letters in a column are not significantly different at 5% probability level.
^{ns}-Not significant, *-Significant at 5% probability level

Root volume

Salinity, Si dosage and variety were the only three factors that significantly influenced rice root volume. Under saline conditions, the root volume was reduced to 10.4 cc as compared to 14.7 cc under saline-control conditions (Table 1). Root volume of rice decreased 29.3% in salinity control and saline treatment. The root volume was 11.7 cc when silicon was applied alone while application of 100 mg Si kg-1 soil led to an increase in root volume to 13.4 cc (Table 1). Therefore, in comparison to Si control, Si treatment led to an increase of 14.5% in root volume. The three varieties have the following root volume: Kalokhoia (14.2 cc); Sadamota (12.8 cc); Sakkorkhana (10.7 cc). Silicon and salt had significant effects on rice root volume (Table 4). The rice root volume was significantly decreased in both Si control and Si 100 mg kg^{-1} soil conditions. Under saline-control, however, the root volume was substantially increased in Si treated plants as compared to saline plants, whereas under saline treatment, no significant differences were observed between the two treatments (Table 4). Again, Table 3 shows that the volume of roots of Sadamota, Kalokhoia and Sakkorkhana was significantly decreased by the salt. It is noteworthy that in saline-control and saline conditions, the traditional variety Kalokhoia had significantly greater root volume compared to other varieties Sadamota and Sakkorkhana (Table 3). The combination between silicon and variety also had a significant impact on rice root volume (Table 4). Sadamota and Sakkhorkhana did not display any evident response to 100 mg Si kg-1 soil but the local variety Kalokhoia had considerably bigger root volume than Si control (Table 4). Under the condition of Si application rate 100mg/kg, Kalokhoia has the highest root volume, while root volume of Sadamota and Kalokhoia is statistically similar in Si control condition (Table 4).

Table 4. Effects of salinity: silicon interactions and silicon: variety interactions on root volume of rice

Interactions	Root volume of rice (cc)		
	Si0 (Control)	Si100	Difference
Salinity:Silicon interactions (n=9)			
Saline-control	12.7	16.5	3.8*
Saline (6 dS m^{-1})	10.5	10.3	0.2^{ns}
Difference	2.2*	6.2*	
Silicon:Variety interactions (n=6)			
Sadamota	12.6 a	13.0 b	0.4^{ns}
Kalokhoia	12.1 a	16.1 a	4.0*
Sakkorkhana	10.1 b	11.1 c	1.0^{ns}

Similar small letters in a column are not significantly different at 5% probability level.
^{ns}-Not significant, *-Significant at 5% probability level

Root dry weight

The dry weight of the root was greatly affected by salinity of the soil, dosage of silicon and rice type. Under saline-control condition, the root dry weight was 3.39 g pot-1 whereas under saline condition, it was 2.54 g pot-1 (Table 1). The root dry weight for Si control was 2.55 g pot-1, which was significantly higher under the 100 mg Si kg-1 soil treatment (3.37 g pot-1). Kalokhoia had the highest root dry weight (3.49 g pot-1) of all the types. Variety and salinity had a significant effect on the dry weight of the rice roots (Table 3). Salinity caused a considerable drop in the root dry weight of the Sadamota and Kalokhoia types. It is interesting to note that the root dry weight of Sakkorkhana didn't considerably reduce with salinity. Nevertheless, the other two types of rice showed lower performance than Kalokhoia under both saline and saline control environments. Silicon application significantly promoted root development and function, by increasing the root volume by 14.5% and the root dry weight by 32.2% compared to the no Si group

Shoot dry weight

Rice shoot dry weight was significantly influenced by salinity, Si dose and variety. Under saline-control condition, 13.7 g pot^{-1}shoot dry weight was noted in rice. Due to salinity shoot dry weight decreased to 10.7 g pot^{-1}, exhibiting 21.9% decrease over saline-control condition. Under silicon control condition the shoot dry weight was 11.7 g pot^{-1} that increased to 12.7 g pot^{-1} when Si was applied at 100 mg kg^{-1} soil rate (Table 1) indicating an increase of 8.55% over silicon control. Among the varieties *Sadamota* produced significantly higher shoot dry weight (14.1 g pot^{-1}), followed by *Kalokhoia* (13.3 g pot^{-1}) and *Sakkorkhana* (9.2 g pot^{-1}) (Table 1). Table 3 shows the significant effect of salinity:variety interaction on shoot dry weight of rice. All the varieties *Sadamota*, *Kalokhoia* and *Sakkhorkhana* significantly reduced the dry weight of shoot under saline condition compared to saline-control condition (Table 3). Under saline-control condition *Sadamota* produced significantly higher shoot dry weight and other two varieties were dissimilar with each other. However, under saline condition *Sadamota* and *Kalokhoia* had statistically similar performance, indicating that the reduction rate of shoot dry weight is higher in *Sadamota* than in *Kalokhoia* (Table 3).

Effects of silicon, salinity, and varieties on rice shoot and root nutrient contents

Root Na^+ content

The salinity effect on Na+ level in the root of rice under saline control was 0.66% and salinity was 0.89% (Table 5). Salt level and the interaction of salt level and silicon strongly affected the Na+ content of the root and shoot of the rice plants (Fig. 1). The Na+ content in rice roots significantly increased under salinity stress conditions irrespective of Si control and Si100 treatments. In contrast, the 100 mg Si kg-1 soil treatment considerably decreased the Na+ level in the root under saline-control conditions, but there was no discernible difference in the Na+ content between the Si control and 100 mg Si kg-1 soil treatment.

Table 5. Na^+ and K^+ content of rice varieties as influenced by silicon application under different soil salinity levels

Factors	Root Na^+ content (%)	Shoot Na^+ content (%)	Root K^+ content (%)	Shoot K^+ content (%)	Root Na^+:K^+ ratio	Shoot Na^+:K^+ ratio
Salinity						
Saline-control (Non-saline)	0.66 b	0.74 b	0.314	1.42 a	2.11 b	0.52 b
Saline (6 dS m^{-1})	0.89 a	1.30 a	0.300	1.26 b	3.01 a	1.05 a
Significance level	***	***	Ns	***	***	***
SE (±)	0.025	0.025	0.012	0.024	0.137	0.022
Silicon						

Si 0 mg kg^{-1} soil	0.78	1.09 a	0.300	1.33	2.63	0.85 a
Si 100 mg kg^{-1} soil	0.77	0.95 b	0.314	1.35	2.49	0.72 b
Significance level	ns	***	ns	Ns	ns	***
SE (±)	0.025	0.024	0.012	0.024	0.137	0.022
Variety						
Sadamota	0.78	0.94 b	0.296	1.34	2.65	0.71 b
Kalokhoia	0.75	0.96 b	0.300	1.35	2.52	0.72 b
Sakkorkhana	0.79	1.17 a	0.324	1.33	2.51	0.92 a
Significance level	ns	***	ns	Ns	ns	***
SE (±)	0.031	0.031	0.014	0.030	0.167	0.027
Significance level of interactions						
Salinity:Silicon (SE ±)	**(0.036)	* (0.036)	ns (0.017)	ns (0.035)	ns (0.193)	** (0.03)
Salinity:Variety (SE ±)	ns (0.04)	***(0.04)	*(0.021)	** (0.04)	ns (0.237)	***(0.04)
Silicon:Variety (SE ±)	ns 0.044)	* 0.044)	ns 0.021)	ns 0.043)	ns 0.237)	* 0.039)
Salinity:Silicon:Variety(SE ±)	ns(0.063)	* (0.062)	ns (0.029)	ns (0.060)	ns (0.235)	* (0.055)
CV%	10.05	7.48	11.87	5.57	16.06	8.67

Note: *, **, *** and ns indicate significant at 5, 1, 0.1 % level, and not significant, respectively. CV- Coefficient of variation; SE- Standard error of means. Similar aesthetic small letters in a column for each single effect are not significantly different at 5% level of probability.

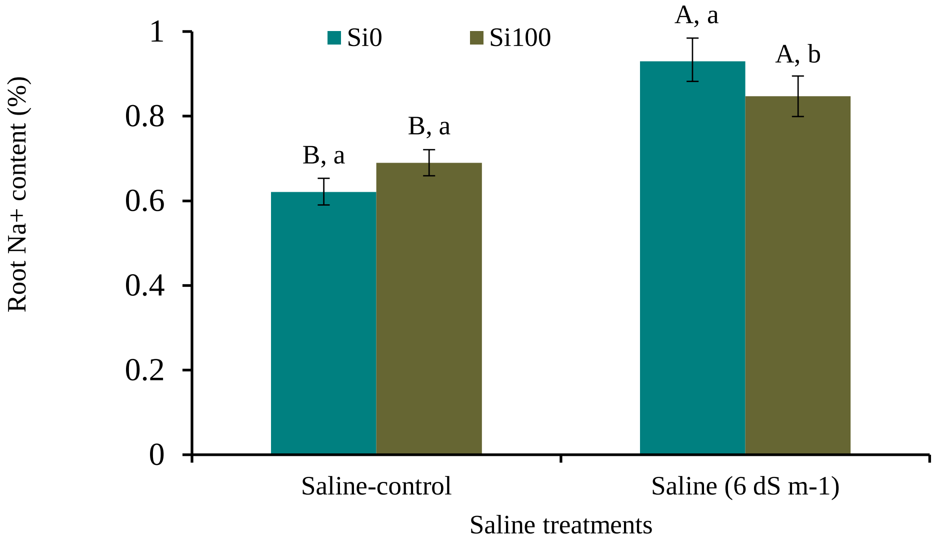

Fig. 1 Effects of Salinity: Silicon interactions on root Na^{+} content of rice (n=6). Aesthetic capital letters compared within the same colour bar at two salinity levels, while small letters compared between two different colour bars within same salinity levels. Vertical bar indicates standard error of means.

Shoot Na^{+} content

Shoot Na^{+} content of rice was significantly affected by salinity, silicon, variety and their interactions (Table 5). Under saline-control condition, the shoot Na^{+} content was 0.74%, which increased to 1.30% in saline condition. The Si control treatment had 1.09% shoot Na^{+} content, while the amount was 0.95% in Si_{100} treatment. Among the varieties, *Sakkhorkhana* had the highest Na^{+} content (1.17%) then *Kalokhoia* (0.96%) and *Sadamota* (0.94%) (Table 5). The significant Salinity: Silicon: Variety interaction effect shows that across the rice varieties and silicon application rates, salinity stress significantly increased the Na^{+} content in shoot (Table 6). In addition, under saline-control condition Si application did not show significant influence on shoot Na^{+} content. However, under saline condition Si_{100} treatment significantly reduced the Na^{+} content in *Sakkorkhana* rice variety, indicating the significant varietal differences in response to Si application (Table 6).

Table 6. Effects of Salinity: Silicon: Variety interactions on shoot Na content of rice

Treatment combinations		Shoot Na content (%)		
		Sadamota	*Kalokhoia*	*Sakkorkhana*
Si0	Saline-control	0.75	0.746	0.846
	Saline (6 ds m^{-1})	1.19	1.29	1.73
	Difference	0.44*	0.54*	0.88*
Si100	Saline-control	0.716	0.636	0.766
	Saline (6 ds m^{-1})	1.09	1.17	1.32
	Difference	0.37*	0.53*	0.55*
Saline-control	Si0	0.75	0.746	0.846
	Si100	0.716	0.636	0.766
	Difference	0.034^{ns}	0.11^{ns}	0.08^{ns}
Saline (6 ds m^{-1})	Si0	1.19	1.29	1.73
	Si100	1.09	1.17	1.32
	Difference	0.10^{ns}	0.12^{ns}	0.41*

^{ns}-Not significant, *-Significant at 5% probability level

Total K+ content in roots and shoots

Only Salinity:Variety interaction was significant for the rice root K+ content (Table 5). Salt had a significant effect on the K+ concentration of rice shoots. The saline condition resulted in a lower K+ content (1.26%) compared to the saline-control condition (1.42%). The increase in K+ content in rice shoots was not significantly different after Si treatment, although there was a positive trend. Table 5 shows that out of all the interactions, only Salinity:Variety was significant.

Na+:K+ ratio in roots and shoots

Exclusive salinity has a substantial effect on root Na+:K+ ratio in rice. Under saline-control conditions, the root Na+:K+ ratio was 2.11, but it increased significantly to 3.01 under saline conditions, which is a 42.7% increase over the saline-control conditions (Table 5). However, no statically significant difference in the effects of silicon, rice variety and their interactions was found. However, salinity, silicon, and crop varieties significantly affected the shoot Na+:K+ ratio of rice, as compared to root. The shoot Na+:K+ ratio became 0.52 under saline-control conditions while it rose over 100% under saline conditions (Table 5). There was a significant effect of the supplement with silicon on the shot Na+/K+ ratio. In contrast, the Si100 treatment decreased the shoot Na+:K+ ratio to 0.72, 15.3% lower than the Si0 (control) treatment. The shoot Na+:K+ ratio of native Sadamota and Kalokhoia varieties were also found to be lowest, i.e. 0.71 and 0.72 respectively and followed by Sakkorkhana variety with Na+:K+= 0.72 (Table 5). Excessive Na+ buildup in rice tissues under saline circumstances upsets K+ homeostasis, resulting in ionic imbalance and metabolic problems. In this study, the shoot Na+ concentration was lowered dramatically by 12.8% and Na+:K+ ratio was lowered by 15.3% for si treated plants compared to the control plants.

Root Si content

The Si content in the shoots of rice plants was noticeably greater with salinity of 4.87% under saline-control and 5.46% under salinity stress condition (Table 7). The silicon application significantly increased the Si content in the shoot as per the single effect with 4.87% Si in the soil control and 5.56% Si in soil with 100 mg Si kg^{-1} soil application. The varieties were also significantly different in Si content showing 5.68, 5.13 and 4.84 % in Sakkorkhana, Kalakhoia and Sadamota, respectively. The significant Salinity:Silicon:Variety interactions indicated that under silicon control condition application of salinity stress significantly increased the shoot Si content in all the tested rice genotypes (Table 9). However, under silicon-applied condition (Si100) only Sakkorkhana variety showed the significant increase in Si content of the shoot. However, Table 9 indicated that under saline-control condition application of 100 mg Si kg-1 soil significantly increased the shoot Si content in Sadamota and Kalokhoia but Sakkorkhana had no significant change. However, Si application had a positive effect on saline situation Sadamota and Sakkorkhana variety (Table 7).

Table 7. Silicon content and uptake of rice varieties as influenced by silicon application at different salinity levels

Factors	Root Si content (%)	Shoot Si content (%)	Root Si uptake (mg pot^{-1})	Shoot Si uptake (mg pot^{-1})	Total Si uptake (mg pot^{-1})
Salinity					
Saline-control (Non-saline)	3.27 a	4.97 b	110.2 a	669 a	779 a
Saline (6 ds m^{-1})	3.09 b	5.46 a	80.2 b	584 b	664 b
Significance level	*	***	***	***	***
SE (±)	0.069	0.107	3.73	17.6	19.1
Silicon					
Si 0 mg kg^{-1} soil	2.99 b	4.87 b	77.5 b	556 b	634 b
Si 100 mg kg^{-1} soil	3.37 a	5.56 a	112.8 a	696 a	809 a
Significance level	***	***	***	***	***
SE (±)	0.069	0.107	3.73	17.6	19.1
Variety					
Sadamota	3.14	4.84 c	100.3 b	675 a	776 a
Kalokhoia	3.20	5.13 b	112.0 a	682 a	794 a
Sakkorkhana	3.19	5.67 a	73.2 c	521 b	594 b
Significance level	Ns	*	***	***	***
SE (±)	0.085	0.131	4.57	21.6	23.4
Significance level of interactions					
Salinity: Silicon (SE ±)	* (0.098)	ns (0.151)	* (5.27)	ns (24.9)	ns (27.1)
Salinity: Variety (SE ±)	ns (0.120)	ns (0.185)	ns (6.46)	ns (30.5)	ns (33.2)
Silicon: Variety (SE ±)	ns (0.120)	ns (0.185)	ns (6.46)	ns (30.5)	ns (33.2)
Salinity: Silicon: Variety (SE ±)	ns (0.170)	* (0.262)	ns (9.13)	ns (43.2)	ns (46.9)
CV%	6.57	6.17	11.75	8.45	7.97

Note: *, **, *** and ns indicate significant at 5, 1, 0.1 % level, and not significant, respectively. CV- Coefficient of variation; SE- Standard error of means. Similar aesthetic small letters in a column for each single effect are not significantly different at 5% level of probability.

Table 8. Effects of Salinity: Silicon interactions on root Si content and uptake of rice.

Treatments	Salinity: Silicon interactions		
	Si0 (Control)	Si100	Difference
Root Si content (%)			
Saline-control	3.17	3.36	0.19^{ns}
Saline (6 ds m^{-1})	2.80	3.37	0.57*
Difference	0.37*	0.01^{ns}	
Root Si uptake of rice (mg pot^{-1})			
Saline-control	97.7	122.6	24.9*

Saline (6 ds m^{-1})	57.3	102.9	45.6*
Difference	40.4*	19.7*	

^{ns}-Not significant, *-Significant at 5% probability level

Shoot Si content

The shoot contents of Si were significantly increased in salinity stress (5.46%) and saline control (4.87%) conditions as compared to rice (Table 7). One single effect showed that the Si content in the shoot was significantly higher in 100 mg Si kg^{-1} soil as compared to Si control at 5.56% and 4.87% respectively. The contents of Si in Sakkorkhana, Kalakhoia and Sadamota were 5.68, 5.13 and 4.84%, respectively, which were significantly different from one another. The salinitySilicon: Variety interactions revealed that all the varieties of rice used had significantly higher shoot Si contents under the silicon control treatment (Table 9). However, the Si content of the shoot increased significantly under silicon-applied condition (Si100) in the case of Sakkorkhana variety. Table 9 revealed that none of the plants demonstrated any significant difference when 100 mg Si kg-1 soil was applied under saline-control conditions, but both Sadamota and Kalokhoia exhibited an appreciable rise in Si content of shoots. However, the varieties of Sadamota and Sakkorkhana grew well in saline condition when treated with Si.

Table 9. Effects of Salinity: Silicon: Variety interactions on shoot Si content of rice

Treatment combinations		Rice varieties		
		Sadamota	*Kalokhoia*	*Sakkorkhana*
Si0	Saline-control	4.03	4.30	5.30
	Saline (6 ds m^{-1})	5.03	5.30	5.26
	Difference	1.00*	1.0*	0.04^{ns}
Si100	Saline-control	4.86	5.46	5.86
	Saline (6 ds m^{-1})	5.43	5.46	6.23
	Difference	0.57^{ns}	0.00^{ns}	0.37*
Saline-control	Si0	4.03	4.30	5.30
	Si100	4.86	5.46	5.86
	Difference	0.83*	1.16*	0.56^{ns}
Saline (6 ds m^{-1})	Si0	5.03	5.30	5.26
	Si100	5.43	5.46	6.23
	Difference	0.40*	0.16^{ns}	1.03*

^{ns}-Not significant, *-Significant at 5% probability level

Root Si uptake

While Si treatment considerably boosted the Si uptake by root (77.5 and 112.8 mg pot-1 in Si0 and Si100, respectively), salinity dramatically decreased the root Si uptake from 110.2 mg pot-1 in saline-control condition to 80.2 mg pot-1 in saline condition (Table 7). Thus, Si treatment increased the uptake of Si in the roots by 45.6% over the Si control. The absorption varied significantly among the kinds of 112.0, 100.3 and 73.2 mg pot-1 for Kalokhoia, Sadamota and Sakkhorkhana respectively. Table 8 shows the significant (5%) Salinity:Silicon relationship. The results showed that the salt stress significantly reduced the root uptake of Si in rice, irrespective of the use of Si. The level of Si uptake by the roots of rice in saline-control and saline conditions, however, was significantly enhanced with silicon administration (100 mg Si kg-1 soil).

Uptake of Shoot Si

The shoot Si uptake of rice was significantly decreased by salinity, 584 mg pot-1 under saline condition and 669 mg pot-1 under saline-control (Table 7). The shoot Si uptake under Si control treatment (Si0) was 556 mg pot-1, whereas it significantly increased to 696 mg pot-1 under treatment of Si100. Hence, the Si treatment increased the shoot Si uptake by 25.2% over Si control. The absorption of Si by the rice varieties Kalokhoia (682 mg pot-1), and Sadamota (675 mg pot-1) were statistically similar while the lowest Si absorption was registered by the variety Sakkorkhana (521 mg pot-1).

Total uptake of Si

The salinity stress resulted in a significant decrease in the total Si absorption (Table 7) from 779 mg pot-1 in saline-control to 664 mg pot-1. The single effect of silicon had a considerable impact on rice's total Si uptake. Si control treatment resulted in the uptake of total Si of 634 mg pot-1 in rice, whereas sprays of 100 mg Si kg-1 soil increased the total Si uptake of rice to 809 mg pot-1. Therefore, Si treatment had increased total Si uptake by 27.6% compared to Si control (Table 7). Kalokhoia showed the highest total Si uptake of 794 mg pot-1, which was statistically similar to Sadamota's total Si uptake of 776 mg pot-1. The lowest concentration was for Sakkhorkhana (594 mg pot-1). For overall Si uptake of rice, there was no significant difference among the interaction (Table 7). Silicon application resulted in 45.6% higher Si uptake than Si control, which indicated that rice sequesters silicon when it is available in soluble form in the soil.

Impact of variety, salinity, and silicon on rice's chlorophyll content

Chlorophyll-a, chlorophyll b and total chlorophyll concentrations of rice leaves did not show significant difference due to the salt although there is a decrease in concentration with salt (Table 10). However, silicon application slightly increased the amount of chlorophyll-a, chlorophyll b and total chlorophyll; unfortunately, it was not significant. Intriguingly, the differences were quite significant between the different chlorophyll granule variations in respect to different chlorophyll granule components. Sakkorkhana variety had the highest total chlorophyll (5.27 mg g-1) and chlorophyll-a (4.00 mg g-1) along with highest chlorophyll b (1.27 mg g-1). Kalokhoia showed minimum chlorophyll content in rice while Sadamota showed second minimum content in rice. Total chlorophyll content, chlorophyll-a and chlorophyll b of rice were not significantly affected by any of the interaction effects (Table 10).

Table 10.Chlorophyll content and uptake of rice varieties as influenced by silicon application under different salinity levels

Factors	Chlorophyll a content (mg g^{-1})	Chlorophyll b content (mg g^{-1})	Total chlorophyll content (mg g^{-1})
Salinity			
Saline-control (Non-saline)	3.85	1.23	5.08
Saline (6 dS m^{-1})	3.79	1.19	4.98
Significance level	ns	ns	Ns
SE (±)	0.067	0.032	0.083
Silicon			
Si 0 mg kg^{-1} soil	3.77	1.16 b	4.93
Si 100 mg kg^{-1} soil	3.87	1.26 a	5.13
Significance level	ns	**	Ns
SE (±)	0.067	0.032	0.083
Variety			
Sadamota	3.79 b	1.21 b	5.00 b
Kalokhoia	3.68 c	1.14 c	4.82 c
Sakkorkhana	4.00 a	1.27 a	5.27 a
Significance level	**	**	***
SE (±)	0.082	0.039	0.102
Significance level of interactions			
Salinity: Silicon (SE ±)	ns (0.094)	ns (0.045)	ns (0.118)
Salinity: Variety (SE ±)	ns (0.116)	ns (0.056)	ns (0.144)
Silicon: Variety (SE ±)	ns 0.116)	ns 0.056)	ns 0.144)
Salinity: Silicon: Variety (SE ±)	ns (0.164)	ns (0.079)	ns (0.204)
CV%	5.26	8.06	4.98

Note: *, **, *** and ns indicate significant at 5, 1, 0.1 % level, and not significant, respectively. CV- Coefficient of variation; SE- Standard error of means. Similar aesthetic small letters in a column for each single effect are not significantly different at 5% probability level

Discussion

Salinity seriously affects rice growth and development, particularly during the reproductive phase, by inducing osmotic and ionic stress that limits water uptake and nutrient balance (Ghosh et al. 2016, Reddy et al. 2017). The present study demonstrated that Si supplementation mitigated these injurious effects in traditional monsoon rice varieties, improving morph-physiological traits and ionic regulation under salinity stress (Ahmad et al. 1992). These results align with previous studies showing the ability of Si to alleviate salinity-induced growth inhibition in rice (Li et al. 2014, Akter et al. 2017, Haque et al. 2023c, Haque et al. 2024b).

Effects on plant growth and morphology

Salinity significantly reduced plant height, tiller number, root volume, and dry biomass, consistent with the well-established inhibitory effects of Na^+ and Cl^- toxicity on cell elongation and division. Silicon application, however, increased plant height by 4.52% and tiller number by 6.93% compared with control. These improvements may result from Si mediated enhancement of cell wall rigidity, maintenance of leaf erectness, and improved water relations, which collectively promote photosynthesis and assimilate partitioning (Haque et al. 2023c, Haque et al. 2024b, Jinger et al. 2022) also reported increased plant height in rice with the increasing dose of Si from calcium silicate. In addition, foliar application of silicon enhances tiller production up to 25%, because of the production of increased auxiliary buds, which clearly rely on the nutritional stability of mother clump causes maximum production of tillers per hill (Flavia et al. 2017). Here, silicon boosts the nutritional status of mother clump thereby total number of tillers per hill was also enhanced.

Root development and dry matter accumulation

Root volume and root dry weight were markedly influenced by Si supplementation, Si increased root volume by 14.5% and root dry weight by 32.2% compared with no Si treatment control, indicating improved root growth and function. Enhanced root development under Si treatment can be attributed to increased cell wall silicification and better mechanical strength, which enable roots to explore a larger soil volume for water and nutrients even under saline stress (Sharma et al. 2021). Similar trends have been reported in rice and other cereals where Si improved root architecture and dry matter accumulation (Jinger et al. 2022, Flavia et al. 2017, Sharma et al. 2021, Siam et al. 2018). Among the tested varieties, *Kalokhoia* showed the highest root dry weight, indicating its superior Si uptake capacity and tolerance to salinity.

Ionic regulation and Na^+ exclusion

Under saline conditions, excessive Na^+ accumulation in rice tissues disrupts K^+ homeostasis, leading to ionic imbalance and metabolic disorders. In the present study, Si application significantly reduced shoot Na^+ concentration by 12.8% and the Na^+:K^+ ratio by 15.3% compared with the control. These findings suggest that Si restricts Na^+ transport from roots to shoots; likely by strengthening the Casparian strip and endodermal barriers, thereby reducing the apoplastic bypass flow of Na^+ (Flam-Shepherd et al. 2018). Silicon supplementation also reduced Na^+ accumulation in rice roots under saline conditions by enhancing the selective uptake of K^+ over Na^+ and strengthening the endodermal barrier; the deduction in Na^+ movement at the aerial parts could be assigned due to the interaction of Na^+ with Si in roots (Ahmad et al. 1992). Calcium silicate exerted positive impacts in alleviating salinity stress through lessening Na^+ accumulation and simultaneously amplifying the accumulation of Si and K^+ in plant tissues (Ali et al. 2018).

Silicon uptake and its physiological implications

Silicon application increased root Si uptake by 45.6% over Si control, confirming that rice, as a Si-accumulating crop, actively assimilates Si when available in soluble form. Enhanced Si accumulation under salinity stress supports cell wall fortification and reduces transpiration losses by forming a silica-cuticle double layer on the leaf epidermis (Li et al. 2014, Ali et al. 2009, Cuong et al. 2017). This layer acts as a physical barrier, limiting excessive Na^+ entry and water loss, thereby improving overall plant water status and turgor maintenance. Additionally, Si enhances nutrient uptake efficiency and boosts tolerance to biotic and abiotic stresses through improved antioxidative defense and metabolic stability (Jinger et al. 2022).

Photosynthetic pigment content and physiological performance

There was no significant effect of silicon and salinity but variety had significant influence on total chlorophyll content of leaf. Previous studies demonstrated that Si enhances chlorophyll retention and photosynthetic activity under stress by reducing oxidative damage and improving light-use efficiency (Flavia et al. 2017, Sivaranjani et al. 2020). The increased chlorophyll content observed in Si-supplemented treatments may be attributed to reduced lipid peroxidation and enhanced Mg uptake, contributing to sustained photosynthetic capacity under saline conditions.

Integrative role of Si under salinity stress

The overall positive impact of Si observed in this study can be attributed to its multifaceted physiological functions: improving plant structure, maintaining ionic balance, reducing Na^+ toxicity, and enhancing root growth and photosynthetic efficiency. The strong correlation between Si uptake and improved K^+:Na^+ ratio in both roots and shoots underscores the integral role of Si in maintain ionic and osmotic homeostasis. At 100 mg Si kg^{-1} soil, the maximum benefit was obtained for all measured traits, indicating this as an optimal level for mitigating salinity stress in traditional monsoon rice. These results collectively demonstrate that Si supplementation enhances the resilience of traditional rice varieties through both structural and physiological mechanisms, offering a sustainable agronomic approach to improving crop performance in saline-prone coastal regions.

Relationship with different plant parameters of rice

Plant height had a strong positive relationship with the root development ($r = 0.74$, $p < 0.001$), and root dry weight ($r = 0.60$, $p < 0.001$), indicating that taller plants were generally supported by better root development. The height of the plants was also found to be positively correlated with the tillers hill-1($r = 0.56$, $p < 0.001$) and the dry weight of the shoot ($r = 0.69$, $p < 0.001$), indicating that the better the root growth, the better the aboveground growth. Similarly, tillers $hill^{-1}$ showed positive correlations with root volume ($r = 0.55$, $p < 0.001$), root dry weight ($r = 0.65$, $p < 0.001$), and shoot dry weight ($r = 0.75$, $p < 0.001$). These relationships suggest that the effects of salinity and silicon were likely to be manifested first in the growth of roots, since the height, tillering and production of biomass of a plant largely depends on its ability to absorb the water and nutrients that are transmitted to the plant through its roots. The parameters involving silicon also helped to establish the significance of root growth in the performance of plants. Total Si uptake had strong positive correlations with root dry weight ($r = 0.85$, $p < 0.001$), shoot dry weight ($r = 0.84$, $p < 0.001$), root Si uptake ($r = 0.87$, $p < 0.001$), and shoot Si uptake ($r = 0.99$, $p < 0.001$). These findings indicate that the better the Si uptake, the better the root growth and the biomass accumulation. Because silicon can enhance root tissue strength and enhance plant tolerance to stress, its positive contribution to shoot growth could have been made through the enhancement of root growth and root function. Conversely, accumulation of Na was negatively related to root and shoot development. Root Na content was negatively correlated with root dry weight ($r = -0.56$, $p < 0.001$), shoot dry weight ($r = -0.59$, $p < 0.001$), and total Si uptake ($r = -0.47$, $p < 0.01$). Shoot Na content also showed significant negative correlations with plant height ($r = -0.79$, $p < 0.001$), tillers $hill^{-1}$ ($r = -0.56$, $p < 0.003$), root volume ($r = -0.67$, $p < 0.001$), root dry weight ($r = -0.62$, $p < 0.001$), and shoot dry weight ($r = -0.69$, $p < 0.001$). These negative correlations suggest that Na accumulation caused by salinity inhibited root growth, which in turn inhibited above-ground growth. On the other hand, shoot K content was positively correlated with plant height ($r = 0.61$, $p < 0.001$), tillers $hill^{-1}$ ($r = 0.34$, $p < 0.05$), root dry weight ($r = 0.43$, $p < 0.01$), shoot dry weight ($r = 0.43$, $p < 0.01$), and total Si uptake ($r = 0.40$, $p < 0.05$)(Table 11). Thus, an improved K accumulation and Si uptake could have assisted in maintaining root activity and facilitating plant growth at salinity stress.

Table 11. Pearson's correlation coefficient between different plant parameters

	PH	TH	RV	RDW	SDW	RSiC	SSiC	RSiU	SSiU	TSiU	RNaC	SNaC	RKC
TH	0.56***												
RV	0.74***	0.55***											
RDW	0.60***	0.65***	0.70***										
SDW	0.69***	0.75***	0.64***	0.80***									
RSiC	0.25ns	0.29ns	0.09ns	0.38*	0.31ns								
SSiC	-0.34*	-0.41*	-0.22ns	-0.27ns	-0.56***	0.19ns							
RSiU	0.59***	0.66***	0.64***	0.96***	0.78***	0.58***	-0.20ns						
SSiU	0.63***	0.63***	0.65***	0.79***	0.83***	0.47**	-0.02ns	0.81***					
TSiU	0.64***	0.65***	0.66***	0.85***	0.84***	0.51**	-0.06ns	0.87***	0.99***				
RNaC	-0.51**	-0.48**	-0.50**	-0.56***	-0.59***	-0.42**	0.40*	-0.58***	-0.42**	-0.47**			
SNaC	-0.79***	-0.56***	-0.67***	-0.62***	-0.69***	-0.41*	0.30ns	-0.64***	-0.62***	-0.64***	0.74***		
RKC	0.15ns	-0.10ns	-0.07ns	-0.10ns	-0.14ns	0.21ns	0.19ns	-0.04ns	-0.05ns	-0.05ns	-0.07ns	-0.18ns	
SKC	0.61***	0.34*	0.37*	0.43**	0.43**	0.39*	-0.24ns	0.46**	0.37*	0.40*	-0.62***	-0.72***	0.40ns

Note: PH-Plant height, TH-Tillers hill^{-1}, RV-Root volume, RDW-Root dry weight, SDW-Shoot dry weight, RSiC-Root silicon content, SSiC-Shoot silicon content, RSiU-Root silicon uptake, SSiU-Shoot silicon uptake, TSiU-Total silicon uptake, RNaC-Root Na content, SNaC-Shoot Na content, RKC-Root K content, SKC-Shoot K content. Note: *, **, *** and ns indicate significant at 5, 1, 0.1 % level, and not significant, respectively.

Conclusions

The results of this study indicates that salinity stress can be alleviated by Si addition in traditional rice varieties grown in the coastal zones of Bangladesh. Besides causing salt accumulation, salinity stress markedly reduced plant height, tillers, root volume and shoot and root dry matter. On the other hand, adding 100 mg Si kg-1 soil significantly improved the growth characteristics, increased total Si uptake by 27.6%, and decreased shoot Na+ concentration and Na+:K+ ratio by 12.8% and 15.3%, respectively. Among the varieties *Kalokhoia* exhibited superior root traits and Si uptake efficiency, reflecting better physiological resilience under saline conditions. These findings confirm the study’s hypothesis that Si supplementation can enhance salt tolerance in traditional rice by improving morpho-physiological performance and ionic regulation. The research contributes new evidence to the limited body of knowledge on Si-mediated stress mitigation in traditional rice genotypes, which are often overlooked despite their genetic diversity and regional importance. However, this pot-based study was conducted under controlled conditions, which may not fully represent field scale soil heterogeneity and long-term salt dynamics. Therefore, extended field evaluations across multiple seasons and soil types are needed to validate the optimal rate and frequency of Si application.

Authors’ contributions

Material preparation, experiment execution, data collection and first draft preparation was done by Umme Kulsum Shanta. Funding, study conception, data presentation, research supervision and manuscript editing were done by Mohammad Asadul Haque. Samsunnahar Pranto, Saimon Islam, Partho Sarker Dhrubo, Montaha Mostafa Soha, and Fatema Nasrin Lamia assisted on data recording and conducted chemical analysis of soil and plant samples. Md Kamal Hossain and Md Fazlul Hoque supervised the research. All authors commented on previous versions of the manuscript. The authors read and approved the final manuscript.

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References

Ahmad, R., Zaheer, S.H., Ismail, S. (1992). Role of silicon in salt tolerance of wheat (*Triticum aestivum* L.), Plant Sci., 85(1) 43–50.

Akter, S., Rahman, M.Z., Rahman, M.M., Nasreen, S.S., Chowdhury, Z.J., Ali, M.A. (2017). Effect of different levels of silicon on yield and yield attributes of rice, Int. J. Nat. Sci. 6(3) 120–122. DOI: https://doi.org/10.13140/RG.2.2.14992.15366

Ali, A., Basra, S.M.A., Ahmad, R., Wahid, A. (2009) Optimizing silicon application to improve salinity tolerance in wheat, Soil Environ., 28(2) 136–144.

Ali, M., Sarwar, G., Afzal, M.S., Muhammad, S. (2018) Physiochemical transformation of waste of super phosphate industry into new generation silicate fertilizer and its uses for rice growth under saline environment, Pak. J. Bot., 50(6) 2091–2095.

Coombs, J., Hind, G., Leegood, R.C., Tieszen, L.L., Vonshak, A. (1985) Analytical Techniques. In: Coombs J, Hall Do, Long SP, Scurlock JMO (Editors), Techniques in Bio-productivity and Photosynthesis. Pergamon Press, 219–228.

Cuong, V.T.X., Ullah, H., Datta, A., Hanh, T.C. (2017) Effects of silicon-based fertilizer on growth, yield and nutrient uptake of rice in tropical zone of Vietnam. Rice Sci., 24 283–290. https://doi.org/10.1016/j.rsci.2017.06.002

Flam-Shepherd, R., Huynh, W.Q., Coskun, D., Hamam, A.M., Britto, D.T., Kronzucker, H.J. (2018) Membrane fluxes, bypass flows, and sodium stress in rice: the influence of silicon, J. Exp. Bot., 69(7) 1679–1692. https://doi.org/10.1093/jxb/erx460

Flavia, B.A. , Brenda, S.T., Murilo, S.M., Lawrence, E.D. (2017) Effect of different silicon sources on yield and silicon uptake of rice grown under varying phosphorus rates, Plants, 6(35) , https://doi.org/10.390/plants6030035

Ghosh, B., Muhammad, N.A., Gantait, S. (2016) Response of rice under salinity stress: A review update, Res Rice, 4: 2. DOI: https://doi.org/10.4172/2375-4338.1000167.

Haque, M.A., Bell, R.W., Jahiruddin, M., Islam, M.N., Kabir, M.E., Sarker, B.C. (2026) NPK fertilization and salinity stress resilience. In: Moulick, D., Sarkar, S., Brahmachari, K. (eds) Salinity Stress and Remediation in Agro-Ecosystems. Springer, Cham. pp 415-434. https://doi.org/10.1007/978-3-032-24001-9_14

Haque, M.A., Bhuyan, M.I., Jahiruddin, M. (2025a) Impacts of plant spacing and nitrogen on wet season rice yield in the non-saline coast of Bangladesh, Int. J. Plant Prod., 19 439–448, https://doi.org/10.1007/s42106-025-00345-3

Haque, M.A., Hoque, M.F (2023) Nitrogen fertilizer requirement and use efficiency in sunflower at Ganges delta coastal salt-affected soils, Commun. Soil Sci. Plant Anal., 54(16) 2248–2262, https://doi.org/10.1080/00103624.2023.2211627

Haque, M.A., Hoque, M.F., Jahiruddin, M., Hossain, M.B., Satter, M. A., Haque, M.E., Bell, R.W. (2023b) Performance evaluation of different sources and rates of silicon in rice at eastern gangetic coastal plains, J. Soil Sci. Plant Nutr., 23 (2023c) 5084–5096. https://doi.org/10.1007/s42729-023-01520-z

Haque, M.A., Jahiruddin, M., Hoque, M.F., Hossain, M.B., Haque, M.E., Bell, R.W. (2025b) Enhancing sunflower yield by identifying phosphorus fertilizer requirements in the Eastern Ganges delta coastal ecosystem, J. Plant Nutr., 48(13) 2217–2237, https://doi.org/10.1080/01904167.2025.2470391

Haque, M.A., Jahiruddin, M., Hoque, M.F., Islam, M.S., Hossain, M.B., Satter, M.A. , Haque, M.E., Bell, R.W. (2023a) Increasing the use efficiency of fertilizer phosphorus for maize in low-p Ganges delta soils, J. Plant Nutr., (46) 2257–2275, https://doi.org/10.1080/01904167.2022.2155544

Haque, M.A., Mobaswera, A., Sume, M.A., Pranto, S., Jahiruddin, M., Hoque, M.F. Bell, R. W.(2024b) Silicon supplementation improves yield and silicon uptake in maize at eastern ganges delta coastal soils, J. Plant Nutr., 47 (2024b) 190–204, https://doi.org/10.1080/01904167.2023.2275066

Haque, M.A., Sima, A.S., Jahiruddin, M., Bell, R.W. (2024a) Minimizing phosphorus mining through optimum phosphorus fertilization in maize, J. Soil Sci. Plant Nutr., (24) 5436–5448, https://doi.org/10.1007/s42729-024-01917-4

Jinger, D., Dhar, S., Dass, A., Sharma, V.K. Paramesh, V., Parihar, M., Joshi, E., Singhal, V., Gupta, G., Prasad, D., Vijaykumar, S.S. (2022) Co-fertilization of silicon and phosphorus influences the dry matter accumulation, grain yield, nutrient uptake, and nutrient-use efficiencies of aerobic rice, Silicon, 14 (2022) 4683-4697. https://doi.org/10.1007/s12633-021-01239-5

Jodder, R., Haque, M.A., Kumar, T., Jahiruddin, M., Rahman, M.Z., Clarke, D. (2016) Climate change effects and adaptation measures for crop production in south-west coast of Bangladesh, Res. Agri. Livest. Fish., (3) 369–378. http://dx.doi.org/10.3329/ralf.v3i3.30727

Khanam, S., Haque, M.A.,, Hoque, M.F., Islam, M.T. (2020) Assessment of salinity level and some nutrients in different depths of soil at Kalapara Upazila of Patuakhali district, Annu. Res. Rev. Biol., 35(12) 1–10, https://doi.org/10.9734/arrb/2020/v35i1230306

Kumar, T., Haque, M.A., Islam, M.S., Hoque, F.M., Jodder, R. (2018) Effect of polythene mulch on growth and yield of sunflower (*Helianthus annuus*), Arch. Crop Sci., (2)38–46, https://doi.org/10.36959/718/600

Li, Z S., ong, Z., Cornelis, J.T. (2014) Impact of rice cultivar and organ on elemental composition of phytoliths and the release of bio-available silicon, Front. Plant Sci., 5 (2014) 529. https://doi.org/10.3389/fpls.2014.00529

Ma, J.F., Yamaji, N. (2015) A cooperative system of silicon transport in plants. Trends Plant Sci., 20(7) 435–442, https://doi.org/10.1016/j.tplants.2015.04.007

Mobaswera, A., Haque, M.A., Sume, M.A., Hoque, M.F. (2023) Exogenous silicon application improves growth and morpho-physiological properties of rice, J. Bangladesh Agric. Univ., (21) 421–429, https://doi.org/10.5455/JBAU.161004

Page, A.L., Miller, R.H. , Keeney, D.R. (1982) Methods of Soil Analysis, American Society of Agronomy, Inc. and Soil Science Society of America, Inc. Madison, Wisconsin.

Pranto, S., Haque, M. A., Hoque, M.F. (2023) Requirement and use efficiency of nitrogen in transplanted Aman rice at Ganges tidal water flooded coastal ecosystem, J. Bangladesh Acad. Sci., 47(2) 169–180, https://doi.org/10.3329/jbas.v47i2.67665

Pranto, S., Haque, M.A., Islam, S., Dhrubo, P.S., Soha, M.M., Lamia, F.N., Rahman, M.L. (2025) Remediation of lead toxicity by exogenous application of silicon in rice, Bangladesh J. Agri., 50(1) (2025) 1–19, https://doi.org/10.3329/bjagri.v50i1.82829

Reddy, I.N.B.L., Kim, B., Yoon, I., Kim, K., Kwon, T. (2017). Salt tolerance in rice: Focus on mechanisms and approaches, Rice Sci., 24(3) 123–144. DOI: https://doi.org/10.1016/j.rsci.2016.09.004

Shanta UK, Haque MA, Akter S, Hossain MK, Hoque MF (2025) Silicon application improves lodging resistance and grain yield of traditional rice genotypes in the coastal ecosystem of Bangladesh. SAARC J Agric 23(2):93–109. https://doi.org/10.3329/sja.v23i2.82981

Sharma, P.P. Jawahar, S., Kalaiyarasan, C., Sriramachandrasekharan, M.V. (2021) Effect of silicon on vegetative growth and root characteristics of rice, Int. J. Botany Stud., 6(4) 09–12.

Shila, A. Haque, M.A. Ahmed, R. Howlader, M.H.K. (2016) Effect of different levels of salinity on germination and early seedling growth of sunflower, World Res. J. Agric. Sci., (3) 048–053.

Siam, H.S., El-Moez, A.M.R. , Holah, S.S., Zeid, A.S.T.(2018) Effect of silicon addition to different fertilizer on yield of rice (*Oryza sativa* L.) plants, J. Appl. Sci., 8(1) 177–190.

Sikder, M.U., Haque, M.A., Jodder, R., Kumar, T., Mondal, D. (2016) Polythene mulch and irrigation for mitigation of salinity effects on maize (*Zea mays* L.), Agric., (14) 01–13, http://dx.doi.org/10.3329/agric.v14i2.31336

Sivaranjani, C., Chithra. L., Baskar, M., Vendan, R.T. Subrahmaniyan, K. (2020) Influence of silicon and nitrogen on chlorophyll content of rice var. TKM-13 in Entisol, J. Pharmacogn. Phytochem., 9(1) 2245–2249.

Sultana, N., Haque, M.A., Hoque, M.F., Hossain, M.B., M.A. Satter, M.A., M. Jahiruddin, M. (2021) Effect of silicon application on growth and biomass yield of rice under salinity stress, J. Bangladesh Agric. Univ., (19) 429–436, https://doi.org/10.5455/JBAU.117294

Sume, M.A., Haque, M.A., Mobaswera, A., Hoque, M.F., Jahiruddin, M., Bell, R. W. (2023) Identifying varietal differences for silicon mediated improvement of leaf architecture and plant growth in rice, Silicon, (15) 6299–6311, https://doi.org/10.1007/s12633-023-02514-3

Yoshida, S., Forno, D.A., Cock, J.H., Gomez, K.A. (1976) Laboratory manual for physiological studies of rice. International Rice Research Institute, Philippines, 3rd ed. pp 17–22.