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SILICON IMPROVES RICE NUTRITION AND PRODUCTIVITY UNDER SALINITY

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Abstract

Silicon (Si) is a beneficial nutrient for plant growth and productivity. Our investigation was conducted to study the influence of Si application for ameliorating the adverse effects of salinity on rice through sodium regulation in plant tissues. Three same textured soils (sandy clay loam) with different electrical conductivity (EC_e: 2.85, 5.28 and 7.57 dS m^{-1}) and pH (8.1, 8.6 and 8.9) were collected at 0-15 cm depth from the Bahauddin Zakariya University Agricultural Farm in Multan, Pakistan. The Si @ 50, 75 and 100 mg kg^{-1} as calcium silicate was applied to pots containing 10 kg sandy clay loam soil (sand 48%, silt 17%, clay 35%). A control without Si application was also maintained. The completely randomized design in 3 × 4 factorial experiment with three replications was established. Thirty days old, seedlings of Kernel Basmati rice were transplanted manually and standard cultural practices were followed. Results showed a significant ($p<0.05$) effect of soil salinity on rice growth and yield parameters. A reduction in grain, straw, leaf and root concentrations of Si, P and K/Na was observed under salinity; however, Si application at 100 mg kg^{-1} ameliorated the salinity stress and significantly increased the root/shoot dry weights, tiller numbers, grain numbers per spike, paddy yield, harvest index, and P and Si concentrations in root, straw, leaves and grains over control though similar to Si @ 75 mg kg^{-1} for shoot dry weight, number of tillers, harvest index, grain/root P concentration and leaf Si concentration. The Si application affected K/Na by increasing K uptake with an associated decrease in Na concentration in plant tissues. Thus, Si application at 100 or 75 mg kg^{-1} soil (200 or 150 kg ha^{-1}) could be a useful strategy for rice production in salt-affected lands. Shoot dry weight, Number of tillers. Harvest index, Grain/root P conc., Leaf Si conc.

Key words: Sodium, Potassium, Harvest index, Factorial, Tillers

Introduction

Soil salinity is a growing concern for crop production worldwide (Acosta-Motos *et al.,* 2017; Munns & Gilliham, 2015). About 800 million ha of productive lands of the world have been turned into salt affected soils (Munns & Tester, 2008). Increased salt concentration in soil solution up to 40 mM NaCl (0.2 MPa osmotic pressure) significantly affects crop growth and productivity (Munns & Tester, 2008) due to accelerated uptake and accumulation of sodium (Na^+) in plant leaves causing chlorosis, necrosis, ion toxicity and disruption in plant physiological processes (Munns, 2002). The severity of salt stress may vary with respect to plant species, climate and soil conditions (Tang *et al.,* 2015). Plant roots serve as the first respondent to Na^+ by showing reduced growth due to osmotic stress and ion toxicity in plant cells (Munns, 2005). These two major threats (osmotic stress and ion toxicity) are associated with excessive concentrations of Na^+ and Cl^- ions which induce deficiency of K^+, Ca^{2+} and other essential nutrients in plants (Marschner, 1995).

Among the cereals (wheat, rice, maize), rice is the second most important staple food crop in Pakistan. Rice seedlings are very sensitive to salinity and show symptoms of stress due to higher transport and accumulation of both Na^+ and Cl^- in leaves (Omisun *et al.,* 2018). Silicon is one of the most abundant elements (about 28%) in soil (Wang *et al.,* 2018). Although, Si is not regarded as one of the essential nutrient elements, it has shown beneficial effects for improving plant growth and development under stress conditions (Hasanuzzaman *et al.,* 2018). Silicon concentration in higher plants may range from 1-10% and even higher in the terrestrial environment (Kumar *et al.,* 2017).

In general, rice is considered as a hyper-accumulator of Si and it can play a key role in rice production (Li *et al.,* 2014). Several investigations have demonstrated the beneficial role of Si in higher plants, including wheat, rice, maize, cucumber, tomato and grasses (Kim *et al.,* 2014)). Recently, Si has been reported to reduce the impacts of various abiotic stresses like heat, drought, heavy metals and salinity on plants (Ashraf *et al.,* 2010; Jang *et al.,* 2018). The role of Si in alleviating salinity stress has been observed in wheat (Tahir *et al.,* 2006), rice (Kim *et al.,* 2014; Tahir *et al.,* 2018) and mung bean (Mahmood *et al.,* 2016, 2017). However, mechanisms by which Si alleviates salinity stress in plants are yet to be established. It is expected that the higher Si content in plants moderated the transpiration rates, and ultimately, decreased the accumulation of salts (Matoh *et al.,* 1986). Our present investigation was an effort to elucidate the beneficial effects of Si application for improving rice growth and yield under salt stress.

Materials and Methods

Experimental conditions: A pot culture factorial experiment [3 soils × 4 Si levels] in completely randomized design with three replications was laid-out in the greenhouse of the Soil Science Department, Bahauddin Zakariya University, Multan. Three soils of different electrical conductivity (EC_e: 2.85, 5.28 and 7.57 dS m^{-1}; pH: 8.1, 8.6 and 8.9, respectively) but of same texture (sandy clay loam: sand 48%, silt 17%, clay 35%) were collected. The soils were air-dried, ground, sieved (2-mm) and homogenized to fill 10-kg in earthen pots (height: 30 cm, diameter: 23 cm). Twelve pots were filled with soil of EC_e 2.85 dS m^{-1}, 12 with soil of EC_e 5.28 dS m^{-1} and 12 with soil of EC_e 7.57 dS m^{-1}. Nitrogen, phosphorus and potassium were applied at the rate of 0.6, 0.3 and 0.3 mg pot^{-1} (120, 60 and 60 kg ha^{-1}) using urea, di-ammonium phosphate, and sulphate of potash, respectively. Si was applied at 0, 50, 75 and 100 mg kg^{-1} soil using calcium silicate. Thirty-day old Kernel Basmati rice paddy was transplanted in the pots. Flooded conditions in pots were maintained using tube well water available at the farm. At maturity, the crop was harvested and the growth and yield parameters were recorded. Harvest index (HI) was calculated by dividing paddy yield with above ground plant biomass. Samples of root, shoot, leaves and seeds were air dried and then oven dried at 65ºC till constant weight and ground prior to chemical analysis.

Nutrient analysis: At random 0.5 g of root/shoot/seed/leaf sample was digested with concentrated H_2SO_4 and H_2O_2 for sodium, potassium and phosphorus contents (Wolf, 1982). The digested dilute aliquots were filtered using Whatman # 42 filter paper and added distilled water to make 50 mL volume. The filtrates were analyzed for Na and K contents by flame photometer and P by UV-Vis spectrophotometer at 420 nm. For Si determination, plant samples were digested with H_2O_2 and NaOH for 2-hr. at 150°C. Si was determined by molybdate-vanadate blue color scheme by UV-Vis spectrophotometer at 650 nm (Elliott & Snyder, 1991).

Data analysis: Data were analyzed statistically through analysis of variance (ANOVA) in two way factorial settings (Steel *et al.*, 1997). Treatment means were compared by Least Significance Difference test at $p \leq 0.05$ (n = 3). Main effects of EC_e and Si, and their interaction ($EC_e \times$ Si) was compared by Least Significance Difference test at $p \leq 0.05$. The statistical analysis was conducted by using statistical software Statistix 8.1® (Analytical Software, USA).

Results

Effect of silicon application on growth and yield of rice under salinity: Salinity showed a gradual decrease ($p \leq 0.05$) in root dry weight (17.9, 15 and 11.7 g/pot, respectively) of rice with increase in soil electrical conductivity (2.85, 5.28 and 7.57 dS m^{-1}) (Table1). On the other hand, increase in Si levels (50, 75 and 100 mg kg^{-1}) increased root dry weight up to 23.6, 48.15 and 79.63%, respectively, as compared to control (without Si). Interaction of Si to salinity (Si × Salinity) significantly affected root dry weight where Si at 100 mg kg^{-1} soil prominently increased root dry weight about 128.57, 75 and 32%, respectively, at all salinity levels (2.85, 5.28 and 7.57 dS m^{-1}) as compared to respective control. Silicon and salinity significantly affected shoot dry weight of rice (Table 1) however their interaction (Si × Salinity) remained non-significant. Shoot dry weight in response to silicon at 75 and 100 mg kg^{-1} remained significantly higher (19.51 and 22%, respectively) over control and at par to each other. Whereas salinity at 7.57 dS m^{-1} showed significant reduction in shoot dry weight (26 and 19%, respectively) over 2.85 and 5.28 dS m^{-1}. Though Si × Salinity interaction remained non-significant even then significantly higher shoot dry weight was recorded for Si at 75 and 100 mg kg^{-1} as compared to respective control but similar to each other.

Table 1. Silicon effects on the dry root/shoot weight, tiller numbers and number of grains per panicle of rice under salinity.

Si treatment (mg kg^{-1})	Root dry weight (g/pot)				Shoot dry weight (g/pot)			
	Soil EC_e (dS m^{-1})				Soil EC_e (dS m^{-1})			
	2.85	5.28	7.57	Si	2.85	5.28	7.57	Si
Control	11.2 fg	10.8 g	10.3 g	10.8 D	20.0 abc	16.7 cd	12.5 e	16.4 C
50	15.1 de	13.6 ef	11.1 fg	13.3 C	20.2 abc	17.5 bcd	15.0 de	17.6 BC
75	19.7 b	16.7 cd	11.5 fg	16.0 B	21.3 a	20.8 ab	16.7 cd	19.6 AB
100	25.6 a	18.9 bc	13.6 ef	19.4 A	21.7 a	20.8 ab	17.5 bcd	20.0 A
Salinity	17.9 A	15.0 B	11.7 C		20.8 A	19.0 A	15.4 B	
LSD	Si (1.5)*, Salinity (1.3)*, Si × Salinity (2.6)*				Si (2.1)*, Salinity (1.9)*, Si × Salinity $(3.7)^{NS}$			
	Number of tillers (per pot)				Number of grains (per panicle)			
Control	25.0 bc	19.8 de	19.2 e	21.3 B	46.9 c	40.4 de	32.9 f	40.1 C
50	27.2 b	22.5 cd	19.7 de	23.1 B	54.0 b	42.7 cd	33.8 f	43.5 B
75	30.7 a	25.8 b	21.2 de	25.9 A	54.9 b	45.1 cd	36.3 ef	45.4 B
100	30.7 a	28.0 ab	21.5 de	26.7 A	63.1 a	54.0 b	44.8 cd	54.0 A
Salinity	28.4 A	24.0 B	20.4 C		54.7 A	45.6 B	37.0 C	
LSD	Si (1.8)*, Salinity (1.6)*, Si × Salinity $(3.1)^{NS}$				Si (2.9)*, Salinity (2.5)*, Si × Salinity $(5.1)^{NS}$			
	Paddy yield (g/pot)				Harvest index			
Control	18.0 cde	12.3 gh	10.0 h	13.4 D	33.3 ef	30.4 f	26.1 g	33.3 B
50	20.0 bc	15.5 ef	11.6 h	15.7 C	37.2 cd	36.3 cde	30.3 f	35.9 AB
75	22.6 ab	16.9 de	12.8 fgh	17.5 B	41.4 ab	37.5 c	33.5 def	38.1 A
100	25.5 a	18.9 cd	15.1 efg	19.8 A	44.4 a	39.2 bc	35.8 cde	36.4 AB
Salinity	21.5 A	15.9 B	12.4 C		39.3 A	34.9 B	33.7 C	
LSD	Si (1.74)*, Salinity (1.51)*, Si × Salinity $(3.01)^{NS}$				Si $(4.6)^{NS}$, Salinity (4.0)*, Si × Salinity $(8.0)^{NS}$			

Means sharing similar letters are statistically at par to each other at $p \leq 0.05$.
NS = Non-significant, Star (*) = Significant

Table 2. Effects of silicon application on sodium (Na), potassium (K), phosphorus (P) and silicon (Si) concentration of rice grain under salinity.

Si treatment (mg kg^{-1})	Grain P conc. (%)				Grain Si conc. (%)			
	Soil EC_e (dS m^{-1})				Soil EC_e (dS m^{-1})			
	2.85	**5.28**	**7.57**	**Si**	**2.85**	**5.28**	**7.57**	**Si**
Control	0.44 b	0.35 c	0.20 e	0.33 C	0.15 c	0.06 e	0.02 f	0.08 D
50	0.49 a	0.41 b	0.20 e	0.37 B	0.19 b	0.13 cd	0.06 e	0.13 C
75	0.50 a	0.42 b	0.29 d	0.40 A	0.20 ab	0.14 cd	0.11 d	0.15 B
100	0.51 a	0.44 b	0.30 d	0.42 A	0.22 a	0.20 ab	0.13 cd	0.19 A
Salinity	0.48 A	0.40 B	0.25 C		0.19 A	0.13 B	0.08 C	
LSD	Si (0.02)*, Salinity (0.02)*, Si × Salinity (0.04)^{NS}				Si (0.02)*, Salinity (0.02)*, Si × Salinity (0.03)^{NS}			
	Root P conc. (%)				**Root Si conc. (%)**			
Control	0.54 c	0.43 de	0.35 g	0.44 C	0.26 bc	0.11 e	0.02 f	0.13 D
50	1.05 b	0.43 e	0.36 fg	0.61 B	0.29 b	0.24 c	0.14 e	0.22 C
75	1.48 a	0.45 de	0.41 ef	0.78 A	0.34 a	0.26 bc	0.19 d	0.26 B
100	1.50 a	0.48 d	0.43 de	0.81 A	0.34 a	0.28 b	0.24 c	0.29 A
Salinity	1.14 A	0.45 B	0.39 C		0.31 A	0.22 B	0.15 C	
LSD	Si (0.03)*, Salinity (0.03)*, Si × Salinity (0.05)*				Si (0.02)*, Salinity (0.02)*, Si × Salinity (0.03)*			
	Straw P conc. (%)				**Straw Si conc. (%)**			
Control	0.51 d	0.44 e	0.28 g	0.41 D	0.15 c	0.04 d	0.02 d	0.07 D
50	0.63 c	0.45 e	0.30 g	0.46 C	0.24 b	0.05 d	0.02 d	0.10 C
75	0.85 b	0.51 d	0.33 fg	0.56 B	0.27 ab	0.13 c	0.03 d	0.14 B
100	1.05 a	0.52 d	0.35 f	0.64 A	0.30 a	0.16 c	0.05 d	0.17 A
Salinity	0.76 A	0.48 B	0.31 C		0.24 A	0.09 B	0.03 C	
LSD	Si (0.03)*, Salinity (0.02)*, Si × Salinity (0.05)*				Si (0.02)*, Salinity (0.02)*, Si × Salinity (0.04)*			
	Leaf P conc. (%)				**Leaf Si conc. (%)**			
0	0.45 de	0.35 f	0.19 g	0.33 D	0.15 d	0.12 de	0.02 f	0.10 C
50	0.54 c	0.40 ef	0.20 g	0.38 C	0.20 c	0.15 d	0.03 f	0.13 B
75	0.67 b	0.42 ef	0.21 g	0.43 B	0.23 ab	0.20 c	0.09 e	0.17 A
100	0.83 a	0.53 cd	0.22 g	0.53 A	0.25 a	0.20 bc	0.11 e	0.19 A
Salinity	0.62 A	0.42 B	0.21 C		0.21 A	0.17 B	0.07 C	
LSD	Si (0.05)*, Salinity (0.04)*, Si × Salinity (0.08)*				Si (0.02)*, Salinity (0.02)*, Si × Salinity (0.04)^{NS}			

Means sharing similar letters are statistically at par to each other at $p \leq 0.05$.
NS = Non-significant, Star (*) = Significant

Number of tillers was decreased (28.4, 24 and 20.4, respectively) significantly with increase in soil salinity from 2.85 to 5.28 and 7.57 dS m^{-1} (Table 1). Silicon application at 75 and 100 mg kg^{-1} significantly increased number of tillers as compared to control and Si at 50 mg kg^{-1} and remained at par to each other. But the interaction of Si and salinity (Si × Salinity) for number of tillers remained non-significant and undifferentiated. Similarly salinity decreased the number of grains per panicle (54.7, 45.6 and 37, respectively) of rice gradually with increasing soil EC from 2.85 to 5.28 and 7.57 dS m^{-1} (Table 1). Whereas Si application at 50, 75 and 100 mg kg^{-1} significantly improved grain number over control about 8.5, 13.22 and 34.67%, respectively. However, interaction (Si × Salinity) was non-significant even then significantly higher number of grains per panicle (34.54, 33.66 and 36.17%, respectively) were observed at all salinity levels due to Si application at 100 mg kg^{-1} over respective control.

A significant increase in paddy yield was recorded due to Si application over control (17.16, 30.61 and 47.76% due to Si at 50, 75 and 100 mg kg^{-1}, respectively) whereas yields were decreased up to 26 and 42.33%, respectively, at 5.28 and 7.57 dS m^{-1} over 2.85 dS m^{-1} (Table 1). The interaction (Si × Salinity) was non-significant but Si at 100 mg kg^{-1} showed highest increase in paddy yield as compared to respective controls at 2.85, 5.28 and 7.57 dS m^{-1}, respectively. The harvest index remained unaffected by Si application at 50 and 100 mg kg^{-1} over control except Si at 75 mg kg^{-1} with 14.41% increase (Table 1). The interaction of Si with salinity (Si × Salinity) remained nonsignificant though all the Si levels (50, 75 and 100 mg kg^{-1}) and showed significantly higher HI as compared to respective controls at all salinity levels (2.85, 5.28 and 7.57 dS m^{-1}). Whereas increasing salinity (2.85, 5.28 and 7.57 dS m^{-1}) significantly decreased the HI (39.3, 34.9 and 33.7, respectively) of rice.

Phosphorus and silicon concentrations in grains, roots, straw and leaves: A significant decrease in grain P concentration (0.48, 0.4 and 0.25%) was recorded due to increase in salinity levels from 2.85 to 5.28 and 7.57 dS m^{-1}, respectively (Table 2). Similarly Si application at 50, 75 and 100 mg kg^{-1} showed a significant (*$p<0.05$*) increase in grain P concentration (up to 12.12, 21.21 and 27.27%) as compared to control. However, Si levels at 75 and 100 mg kg^{-1} showed similar results for grain P concentration and the interaction of Si to salinity also remained non-significant. Though Si application at all levels (50, 75 and 100 mg kg^{-1}) increased grain P concentration over control at 2.85 and 5.28 dS m^{-1}. Si at 75 and 100 mg kg^{-1} significantly increased grain P concentration as compared to control and Si at 50 mg kg^{-1} under 7.57 dS m^{-1} salinity. Highest grain P concentration was recorded in treatments applied Si at 100 mg kg^{-1} at all salinity levels (about 15.9, 25.71 and 50%, at 2.85 to 5.28 and 7.57 dS m^{-1}, respectively). Soil salinity significantly decreased grain Si concentration with increase in EC from 2.85 to 5.28 and 7.57 dS m^{-1} (Table 2). Whereas Si application at 50, 75 and 100 mg kg^{-1} soil significantly increased grain Si concentration (62.5, 87.5 and 137.5%, respectively) as compared to control. The interaction of Si and salinity remained nonsignificant though Si application at all levels (50, 75 and 100 mg kg^{-1}) showed a significant increase in grain Si concentration as compared to respective control at 2.85 to 5.28 and 7.57 dS m^{-1}, respectively. Highest increase (46.67, 233 and 550%) in grain Si concentration over control was recorded with Si at 100 mg kg^{-1} at 2.85 to 5.28 and 7.57 dS m^{-1}, respectively.

Root P concentration was significantly decreased due to salinity whereas Si application at 50, 75, 100 mg kg^{-1} significantly increased it (38.64, 72.27 and 84%, respectively) as compared to control (Table 2). However, Si at 75 and 100 mg kg^{-1} remained statistically similar to each other. The interaction of Si and salinity remained statistically significant whereas highest root P concentrations were recorded up to 1.50, 0.48 and 0.43% due to Si at 100 mg kg^{-1} followed by Si at 75 mg kg^{-1} (1.48, 0.45 and 0.41%) at 2.85, 5.28 and 7.57 dS m^{-1}, respectively. Soil salinity, silicon application and interaction (Si × Salinity) showed significant effect on root Si concentration (Table 2). Increase in salinity (2.85, 5.28 and 7.57 dS m^{-1}) gradually decreased Si concentration in roots (from 0.31 to 0.22 and 0.15, respectively) whereas increase in Si application (50, 75 and 100 mg kg^{-1}) showed a gradual increase up to 39.13, 100 and 123%, respectively, over control. Highest root Si concentration was observed due to Si at 100 mg kg^{-1} followed by 75 mg kg^{-1} at 2.85, 5.28 and 7.57 dS m^{-1}.

Effect of Si and salinity was significant on P concentration in rice straw as well as their interaction (Table 2). Salinity at 5.28 and 7.57 dS m^{-1} showed decrease in straw P concentration (36.84 and 59.21%, respectively) as compared to 2.85 dS m^{-1}. On the other hand, Si application at 50, 75 and 100 mg kg^{-1} showed significant increase in straw P concentration over control (12.2, 36.6 and 56.1%, respectively). Straw Si concertation was significantly changed with soil salinity, Si application and with their interaction (Si × Salinity) (Table 2). Though sharp decrease on Si concentration in straw was recorded due to increase in salinity from 2.85 to 5.28 and 7.57 dS m^{-1} (0.24, 0.09 and 0.03% Straw Si concentration, respectively) however it was counteracted by Si application with an increase of 42.85, 100 and 142.85%, respectively, due to 50, 75 and 100 mg Si kg^{-1}. Highest Si concentration in straw was recorded for Si application at 100 mg kg^{-1} at 2.85, 5.28 and 7.57 dS m^{-1} soil salinity but in par with Si at 75 mg kg^{-1}.

Leaf P concentration was significantly decreased (32.26 and 66.13%, respectively) with increase in salinity (5.28 and 7.57 dS m^{-1}) as compared to 2.85 dS m^{-1} (Table 2). Silicon application at all rates (50, 75 and 100 mg kg^{-1}) increased leaf P concentration (15.2, 30.3 and 60.6%, respectively) as compared to control. Similarly, the interaction of Si and salinity (Si × Salinity) was significant for improving leaf P concentration. However, highest P concentration in leaf was recorded due to Si at 100 mg kg^{-1} at 2.85 and 5.28 dS m^{-1}. The difference in leaf P concentration due to Si levels remained insignificant at 7.57 dS m^{-1}. Silicon concentration in leaf was significantly decreased under salinity with highest decrease (about 66.7%) at 7.57 dS m^{-1} as compared to 2.85 dS m^{-1} salinity (Table 2). Silicon application at all levels (50, 75 and 100 mg kg^{-1}) showed a significant increase in leaf Si concentration over control where Si at 75 and 100 mg kg^{-1} remained similar. The highest leaf Si concentration was recorded by Si at 100 mg kg^{-1} at all salinity levels but statistically similar to Si at 75 mg kg^{-1}.

K/Na of grain, root, straw and leaves: Soil salinity reduced the values of K/Na (reduced K concentration and increased Na concentration) in grain, root, straw and leaf tissues of rice (Fig. 1a, 1b, 1c, 1d). Application of Si at 50, 75 and 100 mg kg^{-1} increased K/Na in grain (659, 665 and 929%), straw (284, 463 and 525%), roots (39, 43 and 65%) and leaf (159, 437 and 558%), respectively, as compared to control under 7.57 dS m^{-1} salinity. At 2.85 and 5.28 dS m^{-1}, only Si at 75 mg kg^{-1} (103, 110%, respectively) and 100 mg kg^{-1} (35 and 118%, respectively) increased K/Na in straw samples as compared to respective control (without Si). Root K/Na was increased by Si application at 50, 75 and 100 mg kg^{-1} (27, 24 and 49%, respectively) as compared to control at 2.85 dS m^{-1} whereas at 5.28 dS m^{-1} salinity, only Si application at 75 and 100 mg kg^{-1} showed higher K/Na in contrast to control and Si at 50 mg kg^{-1}. Similar results for K/Na were also recorded for leaf tissue (Fig. 1d). Following the similar trend as in other plant parts, the leaves also showed highest K/Na where Si at 100 mg kg^{-1} was applied in soil at all salinity levels (2.85, 5.28 and 7.57 dS m^{-1}).

Pearson correlation of yield parameters and K/Na to Si application: Pearson correlation of silicon concentration in leaves and roots of rice indicated direct and significant ($p \leq 0.05$) dependence of harvest index (86 and 88%), paddy yield (85 and 86%), K/Na in leaves (91 and 89%), and K/Na in roots (88 and 83%), respectively.

Table 3. Pearson correlation of leaf and root silicon concentration to the harvest index, paddy yield, K/Na of root and leaf due to Si application in soil under salinity.

Si conc.	Harvest index	Paddy yield	K/Na in leaf	K/Na in root
Leaf	0.86*	0.86*	0.91*	0.88*
Root	0.88*	0.86*	0.89*	0.83*

Mean interactions are significantly different at 0.05 probability level.

Steric shows (*) the differences are significant

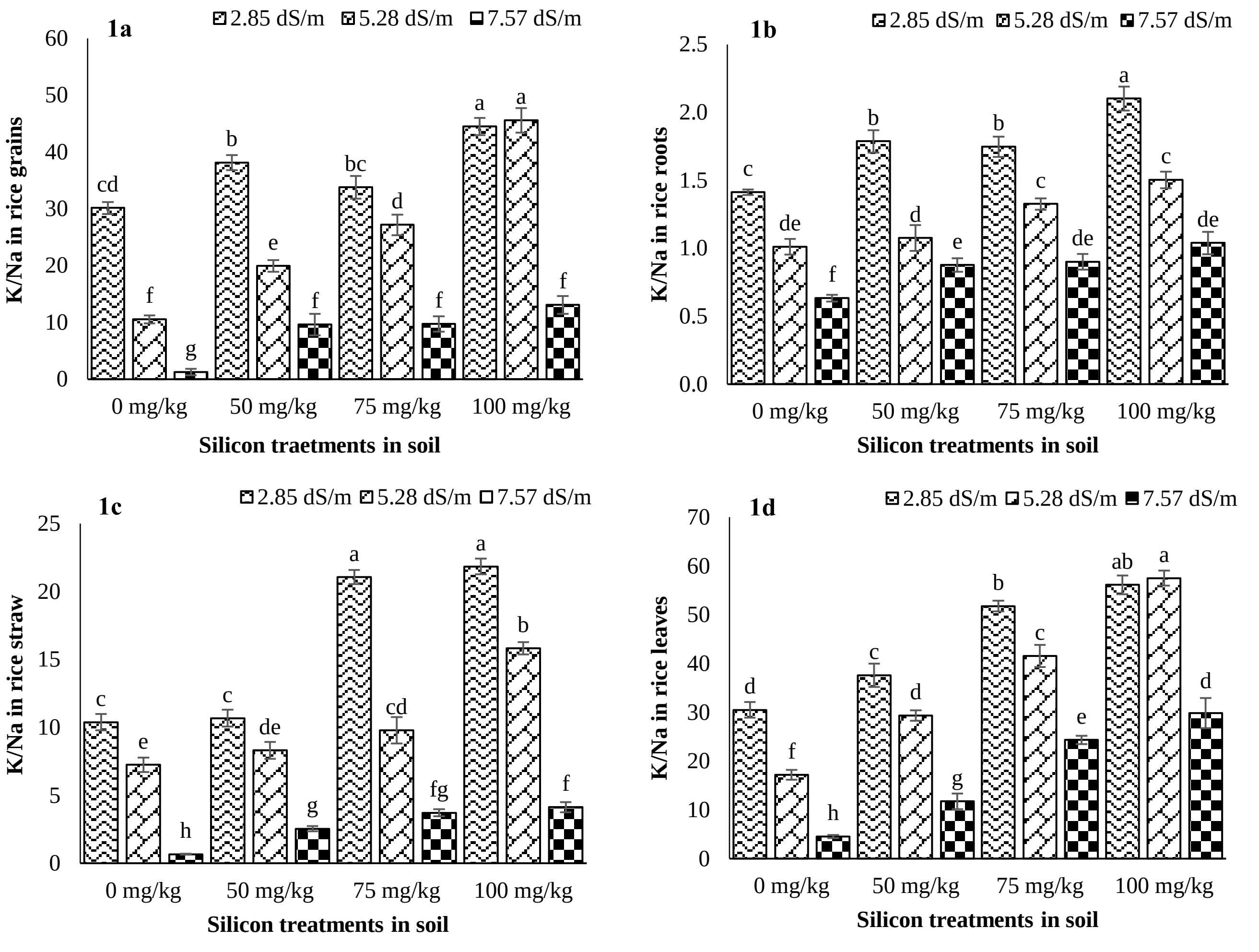

Fig. 1. K/Na in grains (1a) roots (1b), straw (1c), and leaves (1d) of rice influenced by silicon application under salinity.

Discussion

Rice, being a glycophyte suffers salinity particularly at early vegetative and late reproductive stages (Ghosh *et al.,* 2016; Reddy *et al.,* 2017). Whereas Si application can rescue the plant from salinity stress (Ahmed *et al.,* 1992). Rice has been designated as hyper accumulator of Si (Li *et al.,* 2014). Similar results were found when Si application increased Si concentration in rice grain, root, straw and leaf tissues and improved growth attributes under salinity stress (Table 2). Silicon might have mediated increases in antioxidant defense abilities of plants (Hashemi *et al.,* 2010; Kim *et al.,* 2014) and affected ion transport for ameliorating the salt stress induced changes in plants. Silicon treated plants have increased rate of transpiration, high stomatal conductance, higher root hydraulic conductivity and water uptake and accrue Si in roots to reduce Na uptake (Rios *et al.,* 2017). Silicon might have improved rice growth under salinity by decreasing the bypass transport of Na from plant roots to shoots (Flam-Shepherd *et al.,* 2018). A decrease in K/Na was observed in rice tissues (grain, root, straw and leaf) due to Si application under salinity (Fig. 1). Silicon ions significantly attenuated the detrimental physiological and biochemical effects of NaCl on plants (Abdel-Haliem *et al.,* 2017). Moreover, a positive correlation of root and leaf Si concentration to root and leaf K/Na (Table 3) is an indication of increased tolerance of rice to salinity due to decreased Na and increased K concentration in plant tissues by Si application under salinity (Ali *et al.,* 2009). Decreased Na transport in shoots might be due to the complexation of Na with Si in roots (Ahmad *et al.,* 1992). Calcium silicate showed beneficial impacts with increasing rates in ameliorating salinity stress through decreased uptake of Na and increased accumulation of Si and K on plant tissues (Tahir *et al.,* 2006; Ali *et al.,* 2009).

Silicon application increased root/shoot biomass, tillering, paddy yield and harvest index under salinity (Table 1). Shoot dry matter and grain yield had positive linear relationship with shoot Si concentration (Ullah *et al.,* 2017). Foliar application of silicon (0, 2.1, 4.2, 6.3, and 8.4 mg Si/10 plants) to wheat under salinity (2.74, 5.96, 8.85, 10.74, and 13.38 dS m^{-1}) increased the grain yield and N, P, K, and proline concentrations while reducing Na concentrations (Ibrahim *et al.,* 2016). Increased rates of Si application further increased the beneficial effects of Si to plant growth against salinity, as observed in the present study. Pereira *et al.,* (2004) compared 12 Si sources at increasing rates in rice crop and suggested that whatever the sources were, the benefit of Si application increased with rise in its dose. Silicon application diluted the impact of NaCl by increasing the sugar and protein accumulation in Sorghum leaves and increased growth and chlorophyll contents by activating phosphoenolpyruvate (PEP) carboxylase and sucrose synthase activity (Abdel-Latif & El-Demerdash, 2017). Moreover, jasmonic acid might have upregulated the plant genes associated with Si uptake under salinity and activated antioxidant defense systems and induced osmolyte production (Abdel-Haliem *et al.*, 2017). Silicon is beneficial in remarkably affecting physiological phenomena and improving wheat growth under abiotic stress (Alzahrani *et al.*, 2018). Silicon at 100 mg kg^{-1} soil showed highest results in the study for all the parameters whereas Si at 75 mg kg^{-1} remained at par for majority of parameters. The level of 4 mM Si was most effective for mitigating the salt and osmotic stress conditions (Alzahrani *et al.*, 2018). The Pearson correlation of the parameters in the present study strongly supported the relationship of Si concentration in plant roots and leaves for improved productivity and K/Na of the plant tissues under salt affected soils. Silicon application increased the P and Si nutrition of rice (Table 2). Applied Si was readily taken up and accrued in plant tissues (like root, shoot, leaves and grains), increased P nutrition and nitrogen use efficiency with increase in Si supply (Neu *et al.,* 2017). Marodin *et al.,* (2014) suggested that the application of Si using potassium or calcium silicates increased the levels of Si in tomato leaves with increase in crop yield at the highest Si rate (800 kg ha^{-1}).

Calcium silicate application to saline soil at 100 or 75 mg kg^{-1} might be a useful strategy for reducing the impact of salinity on rice while improving plant growth, yield, P, Si and K nutrition by reducing the accumulation or uptake of Na in plant parts.

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