J Bangladesh Agril Univ 23(1): **25–32, 2025** https://doi.org/10.3329/jbau.v23i1.80820

ISSN 1810-3030 (Print) 2408-8684 (Online)

Journal of Bangladesh Agricultural University

Journal home page: http://baures.bau.edu.bd/jbau

Research Article

Soil-Supplied Silicon Alleviates Salinity Stress in Sunflower

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ARTICLE INFO

Article history
Received: 18 December 2024
Accepted: 23 March 2025
Published: 31 March 2025

Keywords
Silicon,
Salt stress,
Mitigation,
Winter crops,
Ion uptake

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Abstract

Silicon (Si), a beneficial metalloid, alleviates various abiotic stresses including salinity. Studies on Si-mediated alleviation of salinity stress of plants were mostly done in solution culture, very rare in soil culture including sunflower. Due to scarce literature on whether soil-supplied Si alleviates salinity stress in sunflower and there is no soil application rate of Si available for sunflower, the current pot study investigated for an optimum Si rate that can ameliorate the salinity effect. The 2-year (2022 and 2023) pot study consisted of two factors: (i) irrigation of crop by ~0 or 8 dS m^{-1} (ii) Si levels, 0, 0.1, 0.2, 0.3 g Si kg^{-1} soil with three replications. The results showed that salinity reduced the yield, yield attributes and dry matter significantly while application of Si gradually increased those yield parameters and seed yield. In case of sodium (Na), potassium (K) and Si uptake, salinity increased Na uptake and reduced K and Si uptake while application of Si decreased the Na uptake but increased the K and Si uptake. Silicon also increased the leaf number per plant and plant height. Among Si levels, 0.2 and 0.3 g kg^{-1} soil showed almost similar ameliorative effect of salinity. The results of the study suggest that soil application of Si can ameliorate salinity stress on sunflower and 0.2 to 0.3 g Si kg^{-1} soil should be suffice to ameliorate the negative effects of salinity. Studies on Si-mediated amelioration of salinity on sunflower and other suitable winter crops should be done in the farmers' field of coastal region of Bangladesh where fresh water is scarce.

Introduction

Worldwide salinity (soil and water) is one of the major abiotic stresses that hampers crop growth and yield as in the southwestern (SW) coastal Bangladesh. The key effects of salt stress on crop plants are (i) osmotic stress (within minutes to hours), (ii) ion toxicity and imbalance (takes days to weeks) (Munns and Tester, 2008). All these effects are usually gone along with oxidative stress, the production of reactive oxygen species (ROS) (Jovanović and Radović, 2021). The simple intervention to ameliorate the deleterious effects of salinity on plant is to flush out salts from the plant root zone by fresh water. Since the availability of fresh water is scarce in the salt affected coastal areas globally and so in SW Bangladesh, options for efficient utilization of this scarce fresh water and mild saline water should be investigated, herein, silicon (Si)-mediated ameliorative investigation could be a potential option by irrigating the crops with low saline water.

Silicon (Si) is a "quasi-essential metalloid" and stress element (Epstein, 1999) that ameliorates many abiotic stresses including salinity (Coskun et al., 2016). Although abundant Si is available in the earth crust (~29% by weight) in different forms, mostly they are unavailable to plants except monosilicic acid, ($Si(OH)_4$), with a typical concentration range between 0.1 to 0.6 mM in soil water (Liang et al., 2015; Coskun et al., 2016) while within plants, this (Si) concentration ranges between 0.1 to 15% of dry weight depending on the species (Taiz and Zeiger, 2010). Silicon deposits as amorphous silica in intracellular spaces, cell lumen, cell wall and trichomes strengthens plant tissue (Epstein, 1999). In salt-stressed crop plants, Si fertilization enhances water retention (Hattori et al., 2005) reduces Na^+ uptake and transportation, enhances K^+ uptake and reduce Na^+/K^+ ratio (Liang, 1999) thus increases crop growth and yield. Since, sunflower is an intermediate accumulator of Si (Tubana and Heckman, 2015), Si-

Cite This Article
Kabir, M.E., Nahid, N.R., Mahmud, A.A. and Ali, M.A. 2025. Soil-Supplied Silicon Alleviates Salinity Stress in Sunflower. *Journal of Bangladesh Agricultural University,* 23(1):25-32. https://doi.org/10.3329/jbau.v23i1.80820

fertilization under saline condition might increase the salt tolerance and thus seed yield.

Our recent research works in SW coastal land of Bangladesh have proved that sunflower fits well as winter crop after harvesting of transplanted (T) aman rice but the seed yield get reduced when irrigated with saline water (Bell et al., 2019; Paul et al., 2020a., Paul et al., 2020b., Paul et al., 2021a; Paul et al., 2021b). While substantial research has been done globally on the effect of Si on salinity tolerance and their underlying mechanisms in solution culture, in Bangladesh, research on this important topic has been overlooked and/or given less emphasis (in both soil and solution culture) although the effect of salt stress on crops is widespread in SW coastal Bangladesh.

Thus Si-mediated alleviation of salinity effect were investigated in the current study. The objectives of the study was to investigate the alleviating effects of soil supplied silicon (Si) on sunflower to modulate the seed yield and ion (Na, K and Si) accumulation under saline condition.

Materials and Methods

The study was conducted in winter 2022 and 2023 following the same experimental material, methods and treatments. Each experiment had two factors.

Factor A was irrigation with saline water with EC ~0 or 8 dS m^{-1}. Factor B was four Si rates to soil (source of Si was silicic acid, powder form). There were three replications thus the treatment combinations were 24.

Hysun 33 was the sunflower variety (hybrid) used in this study. Very few studies are available to examine the response of sunflower to soil application of Si (e.g., Hurtado et al., 2020) However, in clay soil, the recommended application rate was found 0.1753 g Si kg^{-1} soil for rice (Syu et al., 2016). Based on this rate, in the current study, the soil application rates were 0, 0.1, 0.2, and 0.3 g Si kg^{-1} soil.

The experimental non-saline soil was collected from the farmers' field of Pankhali village, Dacope, Khulna. After drying and sieving the soil, different amount of treatment Si and other fertilizers were mixed. Then the experimental plastic pots were filled up with 20-kg soil. Four sunflower seeds were sown in each pot and irrigated immediately by fresh water. The pots were placed under a transparent plastic shed in Dr. Purnendu Gain Field Laboratory, Khulna University, Bangladesh. After emergence and establishment of seedlings (2 weeks), thinning was done keeping one plant per pot. Saline solutions (made from NaCl) were applied starting from low concentration: 2 dS m^{-1} after 2 weeks, 4 dS m^{-1} after 3 weeks, 6 dS m^{-1} after 4 weeks and 8 dS m^{-1} after 5 weeks and the remaining duration when necessary. The 'zero' salinity treatment was irrigated by fresh water. However, the experiments were conducted in a two factors factorial completely randomized design (CRD). Plants were harvested at maturity.

The experiments of the study in each year 2022 and 2023 were started (seed sown) from 2 January and harvested (at maturity) on 1 May in 2022 and 9 May 2023 for the conformity of results and understanding of the response of sunflower to soil-supplied Si under salinity.

In each year data were collected on plant height and leaf number at 25, 40, 55, 70 and 80 days after emergence (DAE); dry matter, yield attributes (head perimeter, seed per plant) and seed yield at maturity. For ion uptake analysis, shoot (leaf and stem) was collected, dried at 70 °C in a forced draft oven for 3 days and then ground to powder. The ground shoot samples were digested in nitric and perchloric acids (3:1) at 150 °C for two hrs. Na and K concentration in shoot were measured by flame photometer (Jenway PFP-7, Germany). The Si in the digested solution was measured by the colorimetric molybdenum blue method at 600 nm (Ma and Takahashi, 2002).

The collected data were analyzed in two-way ANOVA following CRD using the statistical program 'Statistix 10'. The differences between treatment means were separated by Duncuns' multiple range test (DMRT).

Results

Seed yield

In both years, the individual effects of salinity or Si on seed yield were significant (data not shown) and their interaction was also significant ($p<0.01$) (Fig. 1). In general, the seed yield was more in 2022 than that of 2023. Salinity reduced seed yield, however, application of Si at the rate 0.3 g kg^{-1} soil, the seed yield increased 117% in 2022 and 23% in 2023 under non-saline condition compared to zero Si application while under saline condition, Si increased 85% and 36% of seed yield in 2022 and 2023, respectively (Fig. 1). Under saline irrigation, between two years, seed yield was increased more in 2022 than that of 2023.

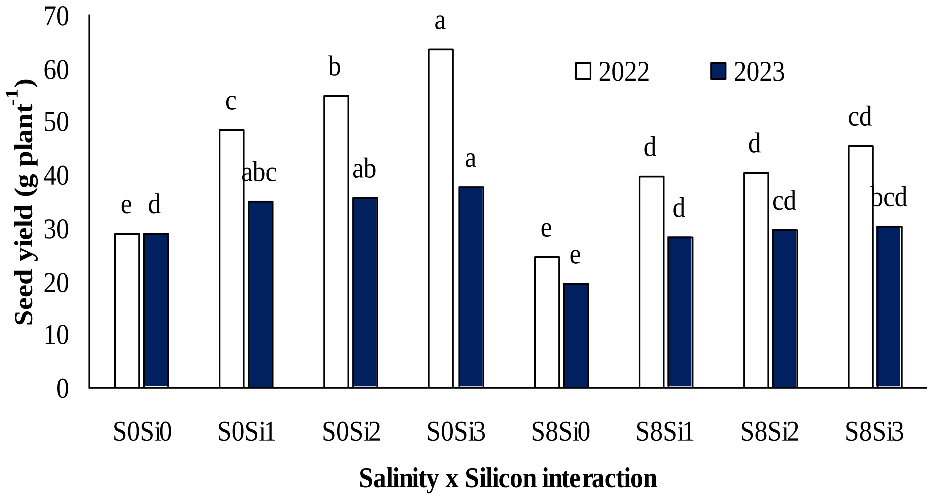

Fig. 1. Seed yield of sunflower as influenced by interaction of silicon and salinity levels in pot experiments in 2022 and 2023. S_0 and S_8 represent the irrigation water salinity of zero and 8 dS m^{-1}, respectively, while Si_0, Si_1, Si_2, and Si_3 represent the 0, 0.1, 0.2, and 0.3 kg Si kg^{-1} soil, respectively. Different letters on each bar signify that the means are different statistically.

Yield attributes and dry matter production

The results of the study demonstrated that individually the saline water irrigation suppressed the yield attributes (head perimeter, seed number per plant) and dry matter production, while supply of Si to soil ameliorated the salinity effect on plant (data of individual effect not shown). Like seed yield, the yield parameters and dry matter (DM) yield was more in 2022 than that of 2023. The interaction of salinity and Si was significant in 2023, the average head perimeter and seed number was 14% and 30% less, respectively, than that of 2022 (Table 1). The dry matter per plant in 2022 was 1.3 to 1.7 times higher (on an average 1.4 times) than that of 2023 (Fig. 2), the yield attributes and DM yield was lowest under zero salinity and zero Si applied treatments (Table 1 and Fig. 2). With the increase in Si amount in both non-saline and saline condition, the yield attributes and DM increased gradually and highest yield attributes and DM was found in 0.3 g kg^{-1} Si which is in most cases was similar to that of 0.2 g kg^{-1} Si.

Table. 1. Yield attributes of sunflower as influenced by interaction of silicon and salinity levels in pot experiments in 2022 and 2023

Treatments	Head diameter		Seed number	
Silicon	2022	2023	2022	2023
S_0Si_0	50.3 de	45.9 c	565 de	442 b
S_0Si_1	60.6 c	52.7 b	607 cd	452 b
S_0Si_2	71.7 a	67.0 a	726 ab	447 b
S_0Si_3	73.1 a	65.0 a	769 a	483 a
S_8Si_0	44.6 e	36.0 d	504 e	404 c
S_8Si_1	56.8 cd	46.7 c	639 c	444 b
S_8Si_2	62.4 bc	54.0 b	648 c	449 b
S_8Si_3	69.2 ab	55.6 b	665 bc	454 b
p value	<0.01	<0.01	<0.01	<0.01
CV (%)	8.8	5.3	7.2	4.3

S_0 and S_8 represent the irrigation water salinity of zero and 8 dS m^{-1}, respectively, while Si_0, Si_1, Si_2, and Si_3 represent the 0, 0.1, 0.2, and 0.3 kg Si kg^{-1} soil, respectively. Different letters in each column signify that the means are different statistically.

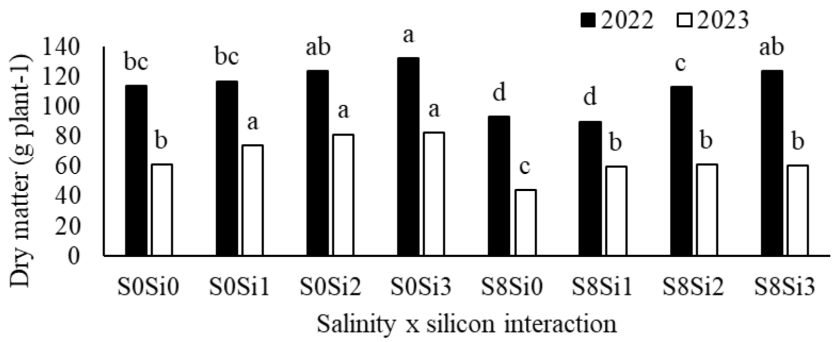

Fig. 2. Dry matter yield of sunflower as influenced by interaction of silicon and salinity levels in pot experiments in 2022 and 2023. S_0 and S_8 represent the irrigation water salinity of zero and 8 dS m^{-1}, respectively, while Si_0, Si_1, Si_2, and Si_3 represent the 0, 0.1, 0.2, and 0.3 kg Si kg^{-1} soil, respectively. Different letters on each bar signify that the means are different statistically.

Ion uptake

Shoot concentration of Na was increased significantly due to individual effect of application of saline water irrigation compared to that of non-saline water in both years: 37% in 2022 and 56% in 2023 (Table 2), i.e., Na uptake was more in 2023. On the other hand, the concentration of K and Si was decreased in both years due to saline irrigation: K concentration was decreased 30% and 25% in 2022 and 2023, respectively, while Si concentration was reduced 32% and 40% in 2022 and 2023, respectively.

The individual effect of addition of Si reduced the shoot Na concentration significantly and the lowest shoot Na was found in 0.3 g kg^{-1} treatment: 8.4 g kg^{-1} in 2022 (21% reduction) and 4.5 g kg^{-1} in 2023 (38% reduction), respectively, compared to their zero Si application values (Table 2). On the contrary, the shoot K and Si concentrations were increased due to increase in amount of Si in 2022 and 2023, the increase in K was 23% and 45%, respectively, the Si concentration was increased 70% in 2022 and 85% in 2023, respectively, compared to their zero Si application values. Due to saline irrigation the Na/K ratio was much higher (Table 2) in both years which was reduced significantly due to application Si (Table 3). The highest Na/K ratio was found in zero Si applied treatment while the lowest ration was observed in highest Si treatment (S_0Si_3) where the highest K was accumulated. The interaction of salinity and Si was non-significant (data not shown).

Table 2. Sodium (Na), potassium (K), silicon (Si) concentration and Na/K ratio of shoot of pot grown sunflower as affected by salinity

Salinity	Na (g kg^{-1})		K (g kg^{-1})		Si (g kg^{-1})		Na/K ratio	
	2022	2023	2022	2023	2022	2023	2022	2023
0	7.6 a	6.3 a	38.2 a	35.3 a	9.1 a	8.3 a	0.20	0.18
8	10.4 b	9.8 b	29.6 b	26.6 b	6.2 b	5.2 b	0.35	0.37
p value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CV (%)	7.3	8.1	9.5	9.5	7.5	6.3	9.6	8.1

S_0 and S_8 represent the irrigation water salinity of zero and 8 dS m^{-1}, respectively. Different letters in each column signifies that the means are statistically different

Table 3. Sodium (Na), potassium (K), silicon (Si) concentration and Na/K ratio of shoot of pot grown sunflower as affected by silicon

Silicon (Si)	Na (g kg^{-1})		K (g kg^{-1})		Si (g kg^{-1})		Na/K ratio	
	2022	2023	2022	2023	2022	2023	2022	2023
Si_0	10.7 a	7.3 a	32.7 d	28.1 c	8.1 c	7.2 d	0.33 a	0.26 a
Si_1	10.4 a	6.4 bc	34.5 c	30.2 c	9.7 c	9.3 c	0.30 a	0.21 a
Si_2	9.5 b	5.3 cd	37.7 b	36.4 b	11.6 b	11.1 b	0.24 b	0.15 c
Si_3	8.4 c	4.5 d	40.2 a	40.7 a	13.8 a	13.3 a	0.21 c	0.11 d
p value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CV (%)	7.3	8.1	9.5	9.8	7.5	6.3	7.4	6.2

Si_0, Si_1, Si_2, and Si_3 represent the 0, 0.1, 0.2, and 0.3 kg Si kg^{-1} soil, respectively. Different letters in each column signifies that the means are statistically different.

The plant height and leaf number

The plant height and leaf number were measured in 25, 40, 55, 70, 84 and 100 DAE but the results of plant height and leaf number were showed only in 55 and 70 DAE (Table 4) because of, in other measuring dates the effect of either salinity or Si and their interaction was non-significant. However, in both years, at 55 and 70 DAE, individual salinity decreased the plant height and leaf number significantly while application of individual Si increased significantly the plant height and leaf number thus data not shown. The interaction of salinity and Si was found significant in plant height at both 55 and 70 DAE (Table 4). In both year the plant height increased gradually with the increase in Si rate and the highest plant height was found in non-saline condition than that of saline condition. In case of leaf number, in 2022, the interaction was found non-significant but at 70 DAE the leaf number showed significant response. At 70 DAE, although there were statistical changes in leaf number, the changes were minor.

Table 4. Plant height and leaf number of sunflower as affected by interaction of silicon and salinity levels in a pot study

Treatments		Plant height (cm)				Leaf number			
		55 DAE		70 DAE		55 DAE		70 DAE	
Salinity	Silicon	2022	2023	2022	2023	2022.0	2023	2022	2023
S_0	Si_0	97.8 bcd	90.1 cd	143.8 bc	100.1 e	31.0	23.0	39.0 ab	32.0 ab
S_0	Si_1	104.3 ab	92.6 bc	147.3 bc	108.5 d	33.2	23.3	39.5 ab	32.3 ab
S_0	Si_2	103.8 abc	94.1 ab	165.0 a	112.9 c	32.5	24.0	40.0 ab	32.7 a
S_0	Si_3	105.5 a	96.1 a	166.2 a	120.0 ab	31.4	24.3	36.5 b	33.0 a
S_8	Si_0	95.5 d	71.7 f	141.2 c	93.6 f	31.5	23.0	38.5 ab	30.0 b
S_8	Si_1	97.2 bcd	83.4 e	148.5 bc	104.3 de	33.3	23.7	41.0 a	32.3 ab
S_8	Si_2	96.5 cd	89.1 d	145.2 bc	116.1 bc	32.5	23.0	40.0 ab	31.0 ab
S_8	Si_3	96.2 d	95.0 ab	154.0 b	123.5 ab	32.4	23.0	37.5 ab	31.3 ab
p value		<0.01	<0.01	<0.01	<0.01	>0.05	>0.05	>0.05	<0.05
CV (%)		6.3	4.3	4.9	4.8	6.7	5.1	6.2	5.1

S_0 and S_8 represent the irrigation water salinity of zero and 8 dS m^{-1}, respectively, while Si_0, Si_1, Si_2, and Si_3 represent the 0, 0.1, 0.2, and 0.3 kg Si kg^{-1} soil, respectively. DAE represents the days after sowing. Different letters in each column signifies that the means are statistically different.

Discussion

The current study showed that irrigation with saline water suppress the plant growth, yield, dry matter accumulation and make imbalance of ion uptake which is historically established responses of plant to salt stress (Munns and Tester, 2008; Ahmed et al., 2024). In the current study, Si ameliorated the suppressive effects of salinity and increased the yield attributes, yield and dry matter of sunflower. It was evident that yield parameters, yield and dry matter was more in 2022 than that of 2023. In 2022, the bottom of the pot, which was perforated, was get touched with fresh water for one day due to leakage of watering pipe near the experimental site. Possibly the root inside the pot absorbed the fresh water, that might reduce the salinity effect, thus, increased the dry matter, grain yield and improved other parameters of plant in 2022. This advantage was not got by the plants in 2023. Probably this is the reason of the wider difference of yield and dry matter between two yeas.

Despite high amount of Si is accumulated in some crop plants which are called Si accumulator e.g., rice, sugarcane, wheat etc., which are the member of Poaceae family and they are monocot (rice, wheat, sugarcane and sorghum under solution culture: Tahir et al., 2012; Liu et al., 2015; Yin et al., 2016), literature is scarce on moderate-Si accumulator, e.g., sunflower, particularly salinity amelioration by soil supplied Si. Moreover, the studies on Si accumulator plants to suppress the salinity effect was mostly done under hydroponic condition (Tuna et al., 2008; Tahir et al., 2012, Liang et al., 2015). So far it is reported that very few studies exist the contribution of Si improving the negative effect of salinity on intermediate Si-accumulator, sunflower (e.g., Hurtado et al., 2020; Ashraf et al., 2015). In the current study the increased yield due to Si application to soil was mainly due to the increase in the size of head (head perimeter) that contained more number of seeds and increased in dry matter with the increase in amount of Si (Table 1, 3). Hurtado et al., (2020) found that Si supply to soil alone or in combination with foliar spray ameliorated the salinity effect by increasing the dry matter, decreasing the uptake of Na and escalating the uptake of K and Si. Although a substantial quantity of Si is available in soil (~29% by weight) in different forms, not all but the monosilicic acid (0.1 to 0.6 mM in soil water) is available for plant (Liang et al., 2015; Coskun et al., 2016). As the source of Si was monosilicic acic and applied at a higher concentration (up to 0.3 g kg^{-1} soil) than the average soil concentration that might help uptake Si by intermediate accumulator (sunflower) of Si to modulate the effects of salinity. As the monosilicic acid is costly and needs higher amount to suppress salinity effect, pot and field studies need further investigations with less costly sources of Si.

The results in solution culture (nutrient solution in washed sand) in attenuating the effect of salinity by applying Si to root showed that Si improved K and Si uptake and increased stem dry matter (Hurtado et al., 2020). Our results on sunflower are also at par with that of Hurtado et al., (2020), Ashraf et al., (2015) and Conceiçao et al., (2019) who supplied Si to soil.

In this study, shoot Si concentration was increased (Table 3). This conforms the previous findings of Liang et al., (2007) and Hutardo et al., (2020). They showed that the Si uptake mechanisms are both active and passive and that Si can be transported in sunflower. Since, numerous studies have showed that when higher concentration of Si exists in the plant growing medium (solution culture) in a soluble form, a high uptake of Si occurs (Epstein, 1999; Ma and Yamaji, 2006). The current study indicates that silicic acid might also present in the root zone of soil at high concentration that facilitated the uptake and transport. In future studies of soil supplied Si, the rhizosphere and bulk soil concentration of Si and its translocation need to be investigated.

Other studies showed that NaCl toxicity was alleviated significantly by increased amounts of Si under salinity (Ahmad et al., 2019). Increased Si concentration might activate major salt tolerant genes that facilities in augmenting Si transportation by the influx and efflux of transporters coded by Lsi1, Lsi2, and Lsi6 (Muneer and Jeong, 2015). The current study showed lower Na concentrations in all Si treatments grown under salinity condition, but lowest Na uptake was found in highest amount of Si applied plants (S_8Si_3). This Si-mediated Na suppression is the most important mechanism for ameliorating salt stress in plants (Epstein, 1999). Our results are in comparison (by Si addition 50 mg kg^{-1} soil; 2 mmol L^{-1} solution) to that of salt-stressed sunflower (Ashraf et al., 2015; Calero et al., 2019). In addition, the lower uptake of Na might be contributed to the accumulation of Si in the pot soil. Several studies showed in high Si accumulating plants that Si deposition decreases Na bypass flow in the growth medium of rice (Flam-Shepherd et al., 2018), sorghum (Yin et al., 2013), wheat (Gurmani et al., 2013). Yin et al., (2016) clarified that polyamine metabolism regulates some important metabolic processes related to ion channel regulation that suppress Na uptake by Si. Bosnic et al., (2018) have also showed that Si suppresses Na accumulation in root that enhances Na exclusion. Although we did not measure root Si concentration, Si in root may decrease the transport of Na to shoots. Si reduces transpiration and deposition of salt as it (Si) deposits and polymerizes small units inside leaves help reducing transpiration and increasing water status of plants; this water dilutes salts in cell and finally alleviate salt damage (Malhotra and Kapoor, 2019).

The significant reduction in shoot K concentration under salinity and Si application increased the shoot K thus reduced the Na/K ratio (Table 3). It is well established that K plays an important role by reducing Na uptake in ameliorating salt damage in plants (Yan et al., 2021). In the current study, the higher concentration of Si showed a higher K accumulation. Liang et al., (1996) showed that Si application increased selectivity of K and decreased that of Na. Studies showed that Si reduces the Na concentration and increases the K concentration in the cytoplasm by increasing the activity of H^+-ATPase enzymes in the plasma membrane (e.g., Xu et al., 2015). In soil, Si increased the K uptake under saline conditions has been reported in sunflower (Ashraf et al., 2015). In solution culture and in other crops, Si increased K uptake in wheat (Tuna et al., 2008; Tahir et al., 2012), and sorghum (Yin et al., 2013). The water status can be improved due to sufficient supply of K (Marschner and Rengel, 2012). Hurtado et al., (2020) suggest in sunflower that Si detoxifies Na probably by stimulating the antioxidative defense mechanism, which may possibly energetically intervene some vital processes of metabolism that increase salt stress tolerance in sunflower. This might be due to improving water status of plant. Because Si increases leaf relative water content (Chen et al., 2018) in salt-affected plants by reducing transpiration rate, although, we did not measure transpiration rate in our study. The deposition of Si in plant tissues forms a mechanical/physical obstacle might have attributed to retention of water in plants (Kumar et al., 2017).

Although Si had a little effect on leaf number but had effect on the size of the leaf (smaller leaf in salt stressed plant) that was reflected in the shoot dry weight of plant in the current study. It is well established that salinity decreases the plant height (Atta et al., 2023) as in the current study but application of Si increased the plant height due to improved physiological and biochemical reactions within the plant (Epstein, 1999).

Thus, our results show that soil supplied Si ameliorated the harmful effects of salt stress developed by saline water irrigation on sunflower. This was due to higher dry matter accumulation, K and Si uptake and suppressing lower Na accumulation because of Si supply to soil. The harmful effects of saline water irrigation were ameliorated more significantly when Si was applied to soil at 0.2 and 0.3 g kg^{-1}. Thus, Si rate of 0.2

to 0.3 g kg^{-1} could be the suggested rate for sunflower to ameliorate salt stress in the SW coastal soil, before that, field study should be done. Since the continued increase in seed yield, dry matter and improving ionic balance with the increase in Si amount (up to 0.3 g kg^{-1}) indicates that application of more than 0.3 g kg^{-1} in future study might increase the seed yield by increasing the dry matter and the uptake of K and Si. As sunflower is well fitted in the SW coastal Bangladesh and saline water (salinity is low during starting of the winter season, high at the end of winter) is available there, sunflower could be cultivated by applying Si at the rate of 0.2 or 0.3 g kg^{-1} soil. Further studies are also necessary regarding Si application from different sources to soil including other sunflower varieties and other crops.

Acknowledgement

The authors acknowledge the Khulna University Research and Innovation Centre for funding the research.

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