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The impact of silicon dioxide on bread wheat seedlings under saline stress

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Abstract

Objective: Silicon has beneficial effects on a wide range of plant species under abiotic stresses. For this reason, investigating the role of silicon in improving the growth of crops under stress has always been of interest.

Methods: This study aimed to investigate the effect of silicon dioxide on seedlings of bread wheat, Pishtaz cultivar. After sterilizing wheat seeds with 70% ethanol, the seeds were planted in pots filled with perlite. The experiment was arranged as factorial based on a randomized complete block design. At the two-leaf stage, silicon dioxide was applied at four levels (0, 15, 30, and 45 mg/l). After one week, salinity stress was applied at two levels of 0 and 100 mM. After one week of applying salt stress, different morphophysiological traits including root and shoot length, root and shoot fresh and dry weight, and content of chlorophyll a, b, carotenoids, sodium, potassium, and iron were measured.

Results: The results showed that salinity has a negative effect on morphophysiological traits, and on the contrary, silicon, especially at a concentration of 45 mg/liter, improves these traits under salt stress. Also, the sodium content in the presence of silicon decreased strongly in the wheat seedlings under salinity, and on the contrary, the K/Na increased. Silicon also had a positive effect on the content of iron and chlorophyll of seedlings under salt stress.

Conclusion: These results show that silicon improves the growth of bread wheat seedlings by facilitating the absorption of mineral elements, homeostasis of nutrients, and preventing the destruction of chlorophyll.

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Introduction

Wheat (*Triticum aestivum* L.) is one of the most important crops in the world, which is considered a sustainable food for about a third of the world's population (FAO 2020). After rice and maize, wheat is the main food of majority of the world's population (Abdelrhim *et al.* 2021). However, the growth and yield of wheat is influenced by various environmental stresses such as drought, salinity, and high temperature (Tahmasebi Shamansouri *et al.* 2018). Salt stress is an environmental threat to all crops worldwide. Currently, millions of hectares of arable land for agriculture are too salty, and hundreds of thousands of hectares of agricultural land are lost for food production due to salinization every year (Harper *et al.* 2021).

Salinity stress initially reduces the absorption of water by the plant by creating osmotic stress and in this way prevents the growth of the plant. Secondly, a large amount of ions enters the plant. When the concentration of ions inside the plant cells increases, the ion homeostasis is destroyed which causes toxicity. At this stage, the second negative effect of salinity on plants is shown, which is called ion toxicity or salt specific effects of salinity (Munns and Tester 2008; Parihar *et al.* 2015). Also, salinity stress reduces photosynthetic activity by increasing the activity of reactive active oxygen species (ROS) and reducing photosynthetic pigments, which ultimately leads to a decrease in the growth and yield of crops (Parida and Das 2005). ROSs are highly reactive and cause damage to lipids, protein, and nucleic acid and generally cause damage to plant metabolism (Ashraf and Harris 2004; Maleki *et al.* 2017).

Due to biochemical, biological, and physiological processes that occur in the plants, they are strongly affected by the presence of excessive salts in the rhizosphere, and consequently, the growth and yield of the plant are strongly affected (Tester and Davenport 2003). To overcome salt stress, the plant tries to reduce the harmful effects of salinity stress by creating defense mechanisms such as the production of various enzymatic and non-enzymatic antioxidants (Weisany *et al.* 2012). In addition to the mechanisms used by the plant, it is possible to improve plant growth under salinity by using supplements such as silicon (Si). Among all of the known trace elements, silicon, which is the most abundant element after oxygen, is the most important mineral element in the soil, and is also known as a useful nutrient that improves seed germination, plant growth, and crop yield (Liang *et al.* 2007; Sabaghnia and Janmohammadi 2015). In addition, the use of silicon increases plant water absorption and transport (Yavaş and Aydın 2017), antioxidant activities (Ma *et al.* 2016), and photosynthetic performance (Wang *et al.* 2019). In addition to improving plant growth, silicon stimulates the resistance mechanisms of plants against biotic (De Curtis *et al.* 2012; Wordell Filho *et al.* 2013) and abiotic (Sabaghnia and Janmohammadi 2014; Sabaghnia and Janmohammadi 2015) stresses. Therefore, in this study, an attempt was made to investigate the effect of different concentrations of silicon on growth of bread wheat seedlings under salt stress conditions.

Materials and Methods

Plant materials and growth conditions

In this study, a bread wheat cultivar, Pishtaz, was used. The seeds were first sterilized using 70% ethanol for 30 seconds and then they were cultivated in pots (15 cm in diameter and 17 cm in height) and under greenhouse conditions. The experiment was conducted in the Graduate University of Advanced Technology's research greenhouse in 2022. Perlite was used as a culture medium. Wheat seedlings were grown in greenhouse conditions using a photoperiod of 16 hours of light/8 hours of darkness and at a temperature of 24 °C at day/18 °C at night. After planting wheat, irrigation was done using water until the seeds germinated. After germination and appearance of greenness, irrigation continued by using the Hoagland solution.

Salt stress treatment

This experiment was conducted as factorial based on the randomized complete block design. The were silicon dioxide at four levels (0, 15, 30, and 45 mg/l) and salt stress at two levels (0 and 100 mM). At two-leaf stage, SiO_2 treatment was applied by dissolving in the Hoagland solution. Hoagland's solution without SiO_2 was used as the control. Three replicates of each treatment were considered. After one week of treatment, salinity stress was applied for seven days.

Measurement of morphological and physiological traits

After seven days of applying salt stress, morpho-physiological traits including root and shoot length, root and shoot fresh weight, root and shoot dry weight, chlorophyll a, b, carotenoids, and sodium, potassium, and iron were measured. The content of chlorophyll and carotenoids was measured according to the method of Wellburn (1994). To measure ions, leaf samples were dried at 72 °C for 48 hours. Then, 0.03 g of completely powdered dry samples was put into the test tubes and after that, 5 ml of acid solution (mixture of 50 ml of HCL with 250 ml of nitric acid) was add. This solution was kept in the room temperature for 24 hours to dissolve the plant sample well in the acid. Then, the resulting solution was passed through a filter paper and made up to 50 ml with distilled water. This solution was used to measure ions in the Varian SpectrAA 220 Atomic Absorption Spectrometer.

Statistical analysis

The data were analyzed using Excel and SAS software. After analysis of variance, Duncan's multiple range tests was used to compare the means.

Results and Discussion

Analysis of variance

The variance analysis revealed that salinity stress affected all traits, except for potassium content and fresh and dry weight of roots, significantly at 0.01 probability level. Also, the effect of silicon dioxide and its interaction with salinity were significant for all traits at least at a 0.05 probability level (Table 1).

Morphological traits

Means of different morphophysiological traits of wheat seedlings grown in different concentrations of silicon dioxide under salt stress are shown in Figure 1. Salt stress (without Si) caused a significant decrease in all morphological traits compared to the control (without NaCl and Si). On the contrary, the addition of silicon dioxide improved the morphological traits under salinity. In the salt-free conditions, the addition of 15 mg/l silicon dioxide caused a 31.7% and 26.4% increase in root and shoot length, respectively. Under the 100 mM of NaCl, 45 mg/l of silicon dioxide caused an increase of 37.4 and 24.1% in root and shoot length, respectively, compared to the control (without Si), (Figure 1A, 1B). The exposure of 15 mg/l silicon dioxide in salt-free conditions and 45 mg/l silicon dioxide in 100 mM NaCl respectively raised root fresh weight by 36.6% and 93.7 %, and shoot fresh weight by 30.1% and 110% correspondingly (Figure 1C, 1D). The root dry weight increased by 37.8% and 98.3% in the presence of 45 mg/l silicon dioxide under 0 and 100 mM NaCl, respectively. Shoot dry weight raised by 14.8% and 25.8% % in the presence of 45 mg/l silicon dioxide under 0 and 100 mM NaCl correspondingly (Figure 1E, 1F).

Physiological traits

Our results showed that under salinity stress and in the absence of silicon, the content of chlorophyll and carotenoid decreases drastically. But by application of silicon, the content of chlorophyll improves (Figure 2). Chlorophyll a content increased by 9.10 and 43.3% in the presence of 45 mg/l silicon dioxide under 0- and 100- mM salinity, chlorophyll b by 7.6% and 87.1%, and total chlorophyll by 8.8% and 70.9%, respectively (Figure 2A, 2B, 2C). However, the carotenoid content increased by 24.8% in the presence of 45 mg/l silicon dioxide in salt-free conditions (Figure 2D).

Table 1. Analysis of variance of the impact of silicon dioxide on wheat seedlings under salt stress for various traits.

Source of variation	df	Mean squares						
		Chlorophyll a	**Chlorophyll b**	**Total Chlorophyll**	**Carotenoids**	**K^+**	**Na^+**	**K^+/Na^+**
Replication	2	0.34	2.61	4.79	0.014	31.70	20.5*	0.46
Salt stress (a)	1	311.5**	693.7**	1935.1**	15.33**	7.74	2879.5**	9.41**
Silicon dioxide (b)	3	5.4**	267.1**	291.4**	1.22**	1644.3**	1619.6**	7.18**
a × b	3	2.9*	82.5**	92.95**	0.819**	3476.5**	2389.0**	3.38**
Error	14	0.62	2.9	3.33	0.025	16.49	5.107	0.166

Table 1 Continued

Source of variation	df	Mean squares						
		Fe	**Root length**	**Shoot length**	**Root fresh weight**	**Shoot fresh weight**	**Root dry weight**	**Shoot dry weight**
Replication	2	0.0038*	0.34	0.38	0.0000002	0.00021	0.000035	0.000009
Salt stress (a)	1	2.78**	24.00**	47.14**	0.000041	0.0108**	0.000016	0.00054**
Silicon dioxide (b)	3	0.41**	13.19**	5.00**	0.00087**	0.00699**	0.00054**	0.00031**
a × b	3	0.0236**	17.41**	38.31**	0.00063**	0.00302**	0.000066*	0.00014**
Error	14	0.00073	0.62	0.371	0.0000147	0.000189	0.000013	0.00003

*,**Significant at 0.05 and.01 probability levels, respectively.

The results of this study showed that the elements' uptake by wheat seedlings is affected by both salt stress and silicon application. Under salt stress (without Si), the content of sodium and potassium ions increased compared to the control (without NaCl and Si), and the K/Na as well as the content of iron decreased sharply (Figure 3). Potassium content increased by 150% and 27.5% in the presence of 15 mg/l silicon dioxide in the salt-free conditions and 30 mg/l silicon dioxide in 100 mM NaCl, respectively (Figure 3A). The highest amount of sodium was observed under salt stress without the presence of silicon dioxide (Figure 3B). Also, the K/Na increased by 54.7% and 371% and Fe content by 44.5% and 90.3% with the use of 15 mg/l of silicon dioxide in the salt-free conditions and 45 mg/l of silicon dioxide in the presence of 100 mM NaCl (Figure 3C and 3D).

Salt stress disrupts cell activities due to increased osmotic stress and ion toxicity, which ultimately suppresses plant growth (Munns *et al.* 2006). Salinity causes changes in plants at the morphological, physiological, and metabolic levels by creating an imbalance in mineral absorption (Kumari *et al.* 2022; Shabala and Munns 2017) and reduced water absorption by plants (Lopez and

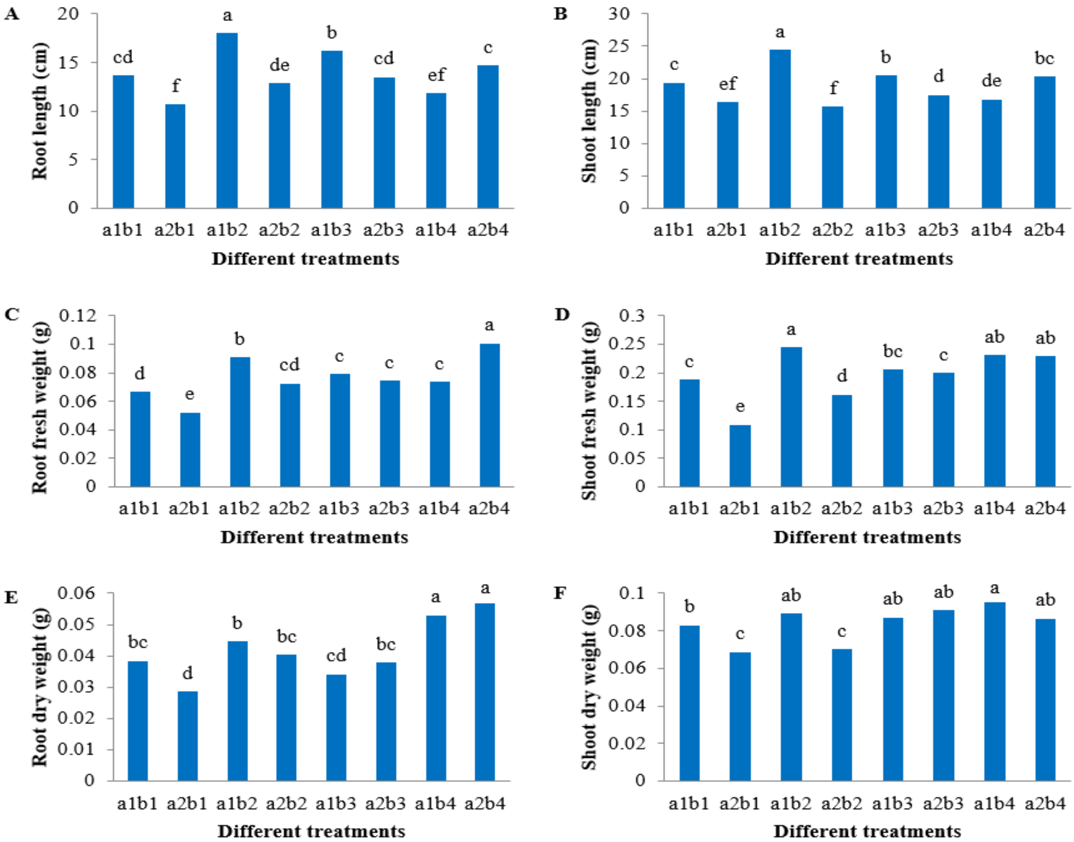

Figure 1. Mean comparisons for the effect of silicon dioxide under salt stress on bread wheat seedlings for root length (A), shoot length (B), fresh weight of root (C), fresh weight of shoot (D) , dry weight of root (E), and dry weight of shoot (F) (a1 and a2 indicate the salinity levels of 0 and 100 mM, respectively, and b1, b2, b3, and b4 indicate the silicon dioxide concentrations of 0, 15, 30, and 45 mg/l, respectively); Means with different letters are significantly different at 0.05 probability level.

Satti 1996). Also, salt stress has an inhibitory effect on plant growth through the reduction of chlorophyll content. Chlorophyll is one of the most important molecules related to photosynthesis, which is responsible for harvesting solar energy and transferring it to photosynthetic complexes (Wang and Grimm 2021). Chlorophyll a is the most abundant form of chlorophyll, which is synthesized from glutamic acid. Chlorophyll b (another form of chlorophyll) is then synthesized from chlorophyll a during the chlorophyll cycle (Tanaka and Tanaka 2006). In fact, chlorophyll content is one of the characteristics that are related to the photosynthetic capacity of plants, which is strongly affected by salinity stress.

Our study showed that the salt stress (without Si) caused a significant decrease in all morphological traits, including root and shoot length, fresh and dry weight at the seedling stage compared to the control (without NaCl and Si), which indicates inhibition of cell division and elongation. The observed reduction in morphological traits in wheat seedlings in response to 100 mM salt stress may be due to the increase in the absorption of sodium ions and the decrease in the K/Na under salt stress (Figure 3B and 3C), which leads to the production of ROS that cause disruption of

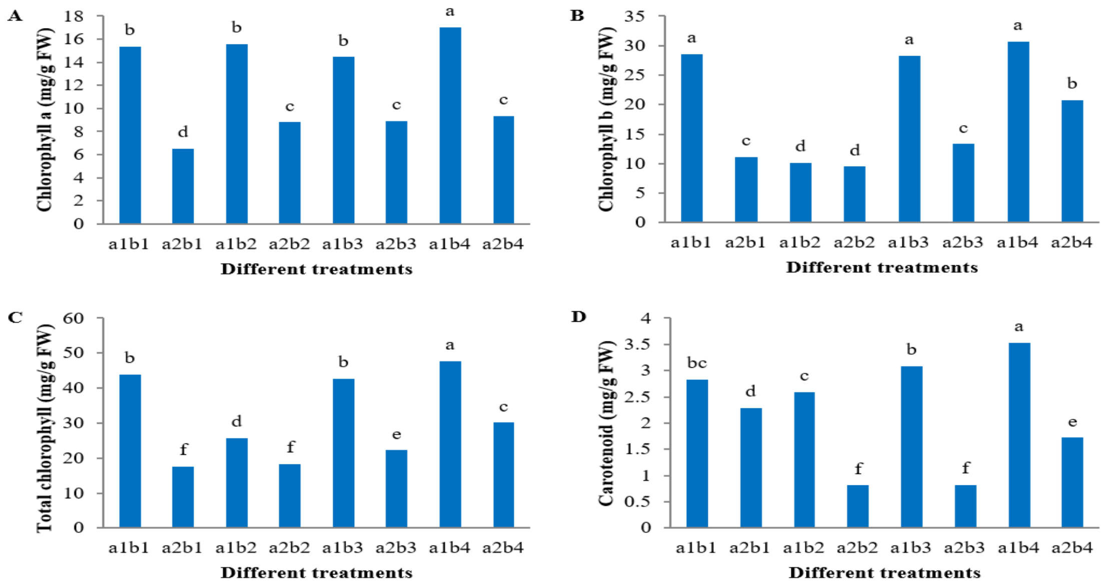

Figure 2. Mean comparisons for the effect of silicon dioxide under salt stress on bread wheat seedlings for chlorophyll a (A), chlorophyll b (B), total chlorophyll (C), and carotenoids (D) (a1 and a2 indicate the salinity levels of 0 and 100 mM, respectively, and b1, b2, b3, and b4 indicate the silicon dioxide concentrations of 0, 15, 30, and 45 mg/l, respectively); Means with different letters are significantly different at 0.05 probability level.

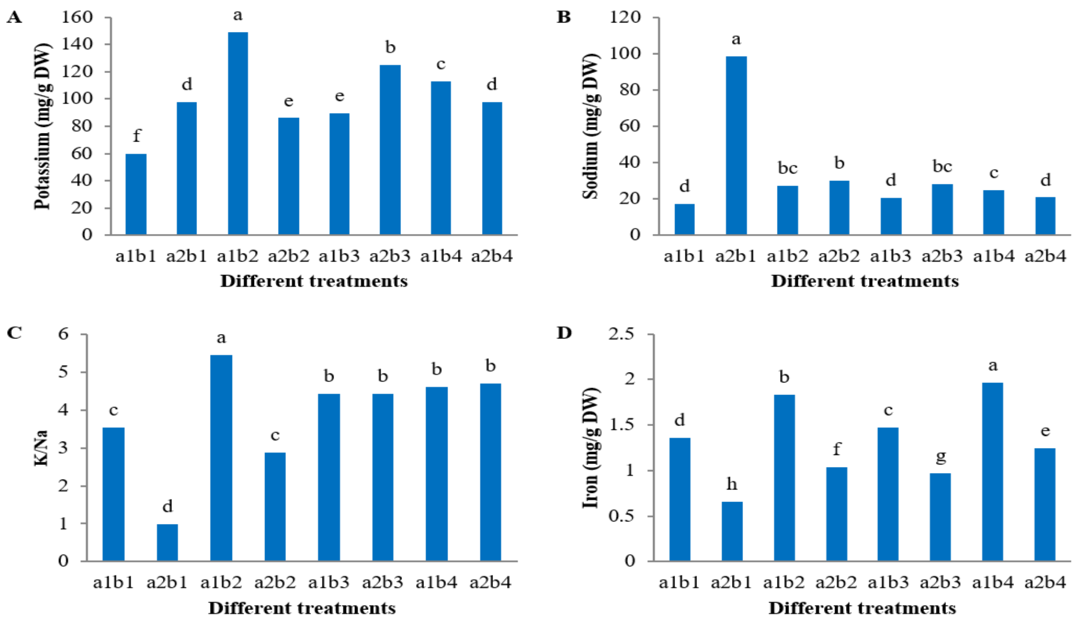

Figure 3. Mean comparisons for the effect of silicon dioxide under salt stress on bread wheat seedlings for Na content (A), K content (B), K/Na (C), and Fe content (D) (a1 and a2 indicate the salinity levels of 0 and 100 mM, respectively, and b1, b2, b3, and b4 indicate the silicon dioxide concentrations of 0, 15, 30, and 45 mg/l, respectively); Means with different letters are significantly different at 0.05 probability level.

the plasma membrane as well as ionic imbalance and thus suppression of metabolic and growth processes (Maleki *et al.* 2017). The results of present study showed that the content of Na^+ and K/Na in the absence of silicon under salt stress increases and decreases, respectively. These results are similar to several studies that have stated ionic imbalance due to the excessive accumulation of sodium ions, which reduces the absorption of other mineral nutrients (Gupta and Huang 2014; Daoud *et al.* 2018). Also, the iron content under salt stress (without Si) decreased drastically compared to the control. In addition to being a part of some proteins and enzymes such as antioxidants, iron also plays an important role in some cellular processes such as photosynthesis. In fact, iron deficiency directly causes chloroplast degeneration and reduced chlorophyll synthesis (Li *et al.* 2021). In this study, the content of chlorophyll a, b, total chlorophyll, and carotenoids also decreased under salt stress (without Si). It seems that the significant decrease in iron content under salt stress can be related to the decrease in chlorophyll content. On the other hand, reducing the chlorophyll content reduces the efficiency of photosynthesis. For this reason, under salt stress, the studied morphological traits have significantly decreased compared to the control.

In our study, silicon treatment improved the morphological traits of wheat seedlings under salt stress compared to the seedlings treated with salt alone (Figure 1). Also, silicon application decreased sodium ion and increased K/Na under salt stress (Figure 3), which ultimately led to the improvement of wheat growth under salt stress. The role of silicon in preventing Na^+ uptake, maintains the homeostasis of nutrients and improves the physiological and morphological characteristics of wheat under salt stress (Javaid *et al.* 2019). Various studies have also shown that the addition of silicon can protect the growth and yield of crops against the harmful effects of salt stress (Watanabe *et al.* 2001; Gong *et al.* 2006; Sienkiewicz-Cholewa *et al.* 2018). The positive effect of silicon on plants is attributed to the effect of this element on the metabolism and transfer of nutrients in plants, which causes higher absorption of them (Linjuan *et al.* 1999; Watanabe et al. 2001). In our study, total chlorophyll increased by 8.8% and 70.9% in the presence of 45 mg/l silicon dioxide under 0 and 100 mM salinity, respectively (Figure 2). In the studies conducted on wheat, mung beans, maize, and grapes, the results show the harmful effects of salinity stress as well as the beneficial effects of silicon treatment on chlorophyll content (Sacala and Durbajlo 2012; Ghassemi-Golezani *et al.* 2015; Mahmood *et al.* 2016; Qin *et al.* 2016; Daoud *et al.* 2018; Sienkiewicz-Cholewa *et al.* 2018). The negative effect of salinity stress on chlorophyll content may be caused by the disruption in chlorophyll biosynthesis or its rapid destruction, while silicon may limit these deleterious changes (Sienkiewicz-Cholewa *et al.* 2018). In the present study, iron content also increased significantly with the addition of silicon dioxide in both control and salt stress conditions (Figure 3D). Considering the role of iron in the synthesis of chlorophyll and ultimately in photosynthesis, it seems that silicon can play an important role in improving the content of chlorophyll under salt stress by improving iron absorption. Finally, the improvement of chlorophyll content is directly related to the improvement of morphological traits.

Conclusion

The results showed that silicon dioxide treatment by reducing Na content and increasing the K/Na maintained the ionic balance and prevented the formation of ROS, and as a result improved various growth traits under salt stress. The increase in iron content and consequently the chlorophyll content in the presence of silicon, the growth of wheat seedlings improved under salt stress conditions. The results of this study show the importance of silicone application in reducing the harmful effects of salt stress in wheat seedlings.

Ethical considerations

The authors avoided data fabrication and falsification.

Conflict of interest

The authors declare that they have no conflict of interest.

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