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Application of silicon ameliorated salinity stress and improved wheat yield

M. A. Ibrahim[1]*, A. M. Merwad[2], E. A. Elnaka[2], C. L. Burras[1] and L. Follett[3]

[1]Agronomy Department, Iowa State University, Ames, IA, 50011 USA.
[2]Soil and Water Science Department, College of Agriculture, Zagazig University, Zagazig, 44511 Egypt.
[3]Statistics Department, Iowa State University, Ames, IA, 50011 USA.

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Management of soil salinity is an important research field around the globe, especially when associated with the limited water resources. This work aimed to improve the growth and yield of wheat (*Triticum aestivum* L. CV. Sakha-93) grown under salinity stress. A completely randomized design pot experiment with three replications was conducted in a loamy soil with various levels of salinity under local weather conditions. The treatments included five levels of salinity (2.74, 5.96, 8.85, 10.74, and 13.38 dSm^{-1}) prepared by adding NaCl to the selected soil and five treatments of Si (0, 2.1, 4.2, 6.3, and 8.4 mg Si/10 plants). Silicon was applied to wheat plants as a foliar spray 30, 45, and 60 days after sowing. Results indicated that photosynthetic pigments; N, P, and K concentrations; biomass, and grain yield significantly decreased with increasing salinity concentration. For example, in the pots treated with Si rate of 0.0 mg Si/10 plants, biomass and grain yield significantly decreased by 37 and 30%, respectively, as salinity increased from 2.74 to 13.38 dSm^{-1}. However, Na and proline concentrations increased with the increase in salinity. Supplying Si alleviated salinity stress and enhanced plant growth, e.g., at salinity concentration of 5.96 dSm^{-1}, biomass and grain yield increased by 32 and 54%, respectively, when Si rate increased from 0.0 to 6.3 mg Si/10 plants. Similarly, under the same previous salinity and Si treatments, Na and proline concentrations decreased by 10 and 23%, respectively. Eventually, application of Si to wheat enhanced its growth and yield under salinity stress.

Key words: Biomass, proline, grain yield, sodium, chlorophyll.

INTRODUCTION

Salinity, in a global scale, is a major limiting factor of negatively impacting plant growth and productivity (Kaya et al., 2003; Shahi et al., 2015). Salinity affected soils occupy ~ 800 million ha worldwide (or ~ 6% of the world's total arable land area) (Munns, 2005). In Egypt, salinity affected soils cover approximately 900,000 ha (or, 32% of the total arable land area) (Ibrahim and Lal, 2013). In salinity conditions, a reduction in plant growth, photosynthesis activity, stomata closure, biomass yield, and nutrients concentrations in the plant tissues occur

*Corresponding author. E-mail:aboaoab@gmail.com. Tel: +1(605) 690-9174.

due to water deficit caused by osmotic imbalance (Parida and Das, 2005; Rahnama et al., 2010). Different strategies have been used to alleviate salinity stress and enhance plant tolerance to it. Applying Si to plants, as one of these strategies, has been used during the past few decades.

After oxygen, Si is considered the second most abundant element in the earth's crust comprising ~ 28% by weight (Wedepohl, 1995). Although total Si is abundant in soil, most of it may not be available to plants. Plants take up Si in the soluble form of mono-silicic acid ($Si(OH)_4$), which occurs in low concentrations in the soil solution (Mitani et al., 2005). Its concentration in most of the soils may range from <1 to 200 mg Si kg^{-1} soil (Ibrahim and Lal, 2014). Several decades ago and based on the criteria suggested by Arnon and Stout (1939), Si was not considered an essential element for plants (Epstein, 1994). In 2005, however, Epstein and Bloom defined new criteria of the essential elements for higher plants upon which Si should be considered an essential element. Although considering Si as an essential element for higher plants is still in debate, it has been stated to be beneficial to alleviate biotic (e.g., plant diseases) and abiotic stresses (e.g., salinity, lodging, drought, freezing, and aluminum toxicity) (Liang et al., 2007; Van Bockhaven et al., 2013). Zhu and Gong (2014) reported that Si does not pollute the environment even when applied in higher quantities than what is required.

Plants take up Si through their roots from soil solution in the form of mono-silicic acid, which is transferred to shoots via xylem and finally precipitates as phytoliths, or plant opal in the cell walls, trichomes, and intracellular spaces (Cooke and Leishman, 2011). It was suggested that Si can be taken up by plant roots either actively or passively, or both of the two ways may coexist for the same plant (Henriet et al., 2006).

Applying Si to wheat improves photosynthetic activity. Tuna et al. (2008) in their pot experiment found a decrease in chlorophyll pigment concentration of two wheat cultivars under salinity stress compared with normal conditions. However, by applying Si, chlorophyll pigments increased under normal conditions as well as under salinity stress conditions. Researchers found salinity stress to hinder plants from absorbing nutrients, e.g., nitrogen (N), phosphorus (P), and potassium (K) resulting in reducing these nutrients concentrations in plant tissues (Reda et al., 2011). During stress conditions, plants tend to increase proline concentration in their tissues in order to facilitate water uptake and maintain osmotic balance (Filippou et al., 2014). Under salinity stress, plants take up Na^+ in higher amount than that is needed and accumulate it in their tissues, which causes detrimental effects on the plant growth and yield (John et al., 2003). However, applying Si to saline soils resulted in declining the amount of Na^+ taken up by plants (Wang and Han, 2007). We hypothesized that application of Si to wheat would increase its tolerance to salinity stress through decreasing Na uptake, increasing N, P, K uptake, and decreasing the formation of amino acid proline in plant tissue. The aims of this work were to (1) assess the impacts of salinity stress on wheat growth, biomass, grain yield, nutrients concentrations in tissues, the uptake of nutrients in straw and grains and (2) assess the effect of silicon application on ameliorating salinity stress and improving plant growth and productivity.

MATERIALS AND METHODS

Experiment set up and design

A pot experiment was conducted in a wired greenhouse under local weather conditions at the College of Agriculture greenhouses, Zagazig University, Zagazig, Egypt. The monthly average temperature rages from 9°C in January to 34°C in July and August and the mean annual precipitation is 51 mm (World Meteorology Organization, 2016). A factorial design with five Si treatments and one soil with five salinity concentrations was used. Pots were arranged in a completely randomized block design with three replicates. Wheat (*Triticum aestivum* L. CV. Sakha-93) seeds were obtained from the Wheat Research Department, Crops Research Institute, Agriculture Research Centre, Giza, Egypt. Seeds were sown on 15 November 2014. Twenty grains were sown in each pot. Each pot was thinned to 10 plants 12 days after sowing.

Five different concentrations of salinity were prepared by mixing a selected soil with NaCl. The selected soil (Haplargids) was collected from the soil surface to a depth of 30 cm from a private farm located in Alhousaynia County, Sharkia, Egypt. The soil was air dried, crushed, and passed through a 5-mm sieve. Closed bottom plastic pots (35 cm in diameter and 30 cm in height) were filled with 10 kg of each air dried soil mixed with NaCl. Soil salinity concentrations were 2.74, 5.96, 8.85, 10.74, and 13.38 dSm^{-1}. Soil salinity was measured using a 1:1 soil: water suspension using an EC meter (Thermo Scientific, Beverly, MA, USA). Sodium chloride was used to adjust salinity concentrations because Na^+ dominates the cations and Cl^- dominated the anions in the selected soil. Each salinity concentration was prepared by adding known weighed amounts of NaCl at different times to a 1:1 soil: water mixture of the original soil that had 2.74 dSm^{-1}. While adding NaCl to the soil, the EC was being measured spontaneously until the desired EC was reached. For example, 1.3 g NaCl was added to a 1:1 soil: water mixture (300 g soil: 300 mL water) to raise the salinity concentration from 2.74 to 5.96 dSm^{-1}, then, the added NaCl weight was calculated to fit 10 kg soil. After mixing the amount of NaCl with the 10 kg soil, a subsample was taken to measure the EC again to make sure the aimed salinity concentration was reached. These particular salinity concentrations were selected in that range because the salt affected soils in Alhousaynia County from which we collected the original soil has these salinity concentrations and even higher.

The highest salinity concentration was selected because plants do not satisfactorily yield at this concentration (Food and Agriculture Organization, 1992). Farmers in this area have been using tile drainage that had different ages and efficiencies resulting in forming different soil salinities. The highest salinity concentration (13.38 dSm^{-1}) was selected because it was the highest concentration at which wheat plants did not die after emergence. Soil chemical and physical properties were determined (Table 1). Soil pH was determined in a 1:1 (soil: water) suspension using an Orion pH meter (Thermo Scientific, Beverly, MA, USA). Particle size analysis (PSA) was determined using the pipette method (Pansu and Gautheyrou, 2006). Soil organic matter was determined using the loss on ignition (LOI) method (Davies, 1974). Inorganic N was

Table 1. Physical and chemical properties of the selected soil.

Sand	Silt	Clay	Texture	pH (1:1)	SIC†	SOM‡	Plant available nutrients		
							N	P	K
	(%)				(g kg^{-1})		mg kg^{-1}		
42.09	32.14	25.77	Loam	8.07	55.13	7.56	67.18	7.54	102.35

† SIC (Soil inorganic carbon), ‡ SOM (Soil organic matter).

extracted by a 2 mol L^{-1} KCl solution and measured using the micro-kjeldahl method (Keeney and Nelson, 1982). Available P was extracted using 0.5 mol L^{-1} $NaHCO_3$ adjusted at pH 8.5. Phosphorus in the extraction was measured colorimetrically at 750 nm wavelength using a spectrophotometer (Milton Roy Spectronic 401, Ivyland, PA, USA) (Watanabe and Olsen, 1985). Potassium was extracted using a 1 mol L^{-1} NH_4OAC solution (Jackson and Barak, 2005) and measured using an atomic absorption spectrometer (PerkinElmer Instruments, Waltham, MA, USA). Soil moisture condition was adjusted by weight to approximately 70% of water holding capacity (WHC).

To each pot, N (as ammonium sulfate) and P (as ordinary super phosphate) were applied at the doses of 90 mg N and 6.5 mg P kg^{-1} soil, respectively. Nitrogen was applied in three equal amounts (each was 30 mg N kg^{-1} soil) at 21 d after sowing, 30, and 60 days after the first dose, respectively. Phosphorus was applied before sowing. Potassium silicate (AgSil 16H, 52.8% SiO_2, PQ Silicates Ltd., Taipei, Taiwan) was used as a source of Si. To prepare the solutions, K-silicate powder was dissolved in distilled water to prepare 10,000 mg Si L^{-1}, from which we made dilutions to prepare the required concentrations (0.0, 140, 280, 420, and 560 mg Si L^{-1}). Five treatments of Si (0.0, 2.1, 4.2, 6.3, and 8.4 mg Si/10 plants) were applied as a foliar spray in three equal amounts (each was one third of the aforementioned Si rates/10 plants) three times during the tillering and booting growth stages 30, 45, and 60 days after sowing. Potassium concentrations in all of the applications were adjusted to be constant using dilute KCl. Distilled water was sprayed to represent the 0.0 mg Si/10 plants. A cardboard box was used during the Si application to protect other pots via separating the pot under application.

Physiological characteristics

After 75 days from sowing (at the booting stage), the fourth and fifth leaves from the base to the apex were collected from three plants from each plot to determine the chlorophyll pigments (Zadoks et al., 1974). Chlorophyll a, chlorophyll b, and carotenoids were determined spectrophotometrically (Milton Roy Spectronic 401, Ivyland, PA, USA) (Metzner et al., 1965). Basically, 0.1 g of a fresh leaves was ground and extracted with 5 mL 85% (v/v) acetone in a dark room. The contents were filtered and determined at absorbance of 452, 644 and 663 nm alongside a blank of untainted 85% liquid acetone. Chlorophyll pigments were calculated using the equations published by Porra et al. (1989). Proline content was determined using the ninhydrin method established by Bates et al. (1973). Briefly, 0.5 g of fresh leaf tissues was homogenized in 10 mL of 3% sulphosalicylic acid and filtered. In a test tube, 2 mL of the filtered solution was mixed with 2 mL of acid ninhydrin and 2 mL of glacial acetic acid. Contents of the test tube were placed in a water bath at 100°C and left to react for 1 h. Afterwards, the mixture was extracted with 4 mL toluene and measured at 520 nm absorbance using a spectrophotometer (Milton Roy Spectronic 401, Ivyland, PA, USA).

Plant harvesting and preparation:

Five plants from each pot were randomly selected for harvest and weighed (fresh biomass weight). Spikes and shoots were separated. Spikes were threshed manually to obtain the grain yield and conduct the chemical analyses. Straw (leaves and stems) were transferred in paper bags to an oven adjusted at 65°C and left for 3 days until the weight became constant (the biomass dry weight). Dried wheat materials were ground using a Wiley mill (Thomas-Wiley Co., Philadelphia, PA, USA) to pass a 2 mm screen, and were reground to uniformity and pass through a 1 mm screen using a UDY-Cyclone impact mill (UDY Corporation, Fort Collins, CO, USA). All of the ground subsamples were stored in polyethylene bottles for further analyses.

Chemical analyses:

For Si determination, 100 mg of the dried plant tissue materials were placed in a digesting flask containing a mixture of 5 mL concentrated nitric acid, 1 mL 70% perchloric acid, and 0.5 mL concentrated sulfuric acid (Nayar et al., 1975). The flask with its contents was placed on a hotplate (under a hood) for 1 h, or until the brown fumes stopped. The digested solution was quantitatively transferred to a 250 mL measuring flask containing 1.5 g Na_2CO_3. The later flask with its contents was boiled for 5 min, cooled, its volume was made to 250 mL, and transferred to a polyethylene bottle to be stored until determination. Silicon in the stored solution was measured colorimetrically using a spectrophotometer (Milton Roy Spectronic 401, Ivyland, PA, USA) following the molybdenum blue method (Hallmark et al., 1982). To determine Na and K, 0.1 g of the ground and dried plant tissue materials was digested overnight with 25 mL of 0.1 mol L^{-1} HNO_3 in the room temperature (John et al., 2003). Both Na and K were measured using the atomic absorption spectrometer (PerkinElmer Instruments, Waltham, MA, USA). To determine N and P, 0.3 g of ground and dried plant tissue materials was digested with 4 mL concentrated H_2SO_4 and 1 mL of concentrated $HClO_4$. The digested materials were quantitatively transferred to a 100 mL volumetric flask using distilled water. N was determined using the distillation method and a micro-kjeldahl apparatus (Chapman and Pratt, 1982). Phosphorus was determined colorimetrically at 750 nm wavelength using a spectrophotometer (Milton Roy Spectronic 401, Ivyland, PA, USA) (Watanabe and Olsen, 1985).

Statistical analyses

All of the obtained data such as chlorophyll pigments, carotenoids, biomass, grain yield, proline, and concentrations of N, P, K, Na, and Si were statistically analyzed using SAS 9.4 software (SAS Institute, 2011). Two-way factorial ANOVA procedures were carried out using the mixed procedure of SAS with salinity, silicon and the interaction included as fixed effects. Both salinity and silicon were treated as

categorical variables. Orthogonal polynomials were used to compute lack-of-fit tests to determine whether or not salinity or silicon could be included instead as numeric variables for a regression analysis. It was determined that, for many responses, there was significant lack-of-fit for a linear trend for both salinity and silicon. For consistency, we use the same 2-way factorial model with salinity and silicon treated as categorical variables for each response. Treatment means were obtained using the lsmeans and all differences were obtained using lsmestimate statements. Significant differences were determined at a 0.05 level after adjusting for multiple comparisons.

RESULTS AND DISCUSSION

Plant growth characteristics

Salinity was known to be a limiting factor for plant growth and productivity. Our results showed that concentrations of chlorophyll a, chlorophyll b, and carotenoids, within each individual foliar Si rate, decreased with increasing salinity stress. For example, the concentrations of chlorophyll a, chlorophyll b, and carotenoids within the Si rate of 0.0 mg Si/10 plants, significantly decreased as salinity concentration increased from 2.74 to 13.38 dSm^{-1} (Table 2). Similarly, within the Si rate of 4.2 mg Si/10 plants, chlorophyll a and chlorophyll b significantly decreased when salinity concentration increased from 2.74 to13.38 dSm^{-1} (Table 2). Tuna et al. (2008) in their work on influence of silicon application on the characteristics of wheat plants grown under salinity stress found a significant decrease in chlorophyll a and chlorophyll b when salinity concentration increased. This decrease in chlorophyll a and chlorophyll b could be interpreted as a consequence of the formation of proteolytic enzymes, e.g., chlorophyllase, which is responsible for chlorophyll deterioration (Sabater and Rodriquez, 1978). Carotenoids, within the Si rate of 8.4 mg Si/10 plants, significantly decreased as salinity concentration increased from 2.74 to 13.38 dSm^{-1} (Table 2). However, all of the applied Si rates resulted in increasing the content of chlorophyll pigments under every individual salinity concentration. For example, within salinity concentration of 2.74 dSm^{-1}, chlorophyll a, chlorophyll b, and carotenoids significantly increased when Si rate increased from 0.0 to 6.3 mg Si/10 plants (Table 2). Similarly, within salinity concentration of 8.85 dSm^{-1}, chlorophyll a, chlorophyll b, and carotenoids significantly increased as Si rate increased from 0.0 to 6.3 mg Si/10 plants. Similarly, Rios et al. (2014) found an increase in chlorophyll pigments in wheat leaves when Si was applied.

When plants encounter either salinity or drought stresses, proline content increases in their tissues in order to resist these stresses (Filippou et al., 2014). Results in Table 2 revealed that proline concentration, within each Si rate, increased with increasing salinity concentration. For example, within the Si rate of 0.0 mg Si/10 plants, proline concentration significantly increased when salinity concentration increased from 2.74 and 13.38 dSm^{-1}. Similarly, proline concentration significantly increased within the Si rate of 8.4 mg Si/10 plants when salinity concentration increased from 2.74 and 13.38 dSm^{-1} (Table 2). Similar to our results, Tuna et al. (2008) found an increase in proline concentration with increasing salinity concentration. As a consequence of abiotic stresses, amino acids (e.g., proline) accumulate in shoots and roots to act as sinks of excess N (Dubey and Pessarakli, 1995). However, applying Si to plants in these conditions of stress decreased proline concentration, which could be due to the reaction between proline and Si forming silaproline similar to what takes place in the human body (Vivet et al., 2000). Within each salinity level, applied Si decreased proline concentration by increasing Si rate. For example, proline concentration, within salinity concentration of 2.74 dSm^{-1}, significantly decreased when Si rate increased from 0.0 to 8.4 mg Si/10 plants (Table 2). Similarly, within salinity concentration of 13.38 dSm^{-1}, proline concentration significantly decreased when Si rate increased from 0.0 to 8.4 mg Si/10 plants.

In our experiment, plant height decreased with increasing soil salinity within each Si rate. Under Si rate of 0.0 mg Si/10 plants, plant height significantly decreased when salinity concentration increased from 2.74 to 13.38 dSm^{-1} (Table 2). Similarly, under the applied Si rate of 6.3 mg Si/10 plants, plant height significantly decreased when salinity concentration increased from 2.74 to 13.38 dSm^{-1}. This decline in plant height could be due to the decrease in chlorophyll pigments or photosynthetic activity resulting in hindering plant growth. However, applying Si to plants ameliorated the negative impacts of salinity stress on plant height under all of the salinity concentrations, i.e., plant height increased with increasing Si concentration compared with no addition of Si (0.0 mg Si/10 plants) (Table 2). For example, within salinity concentration of 2.74 dSm^{-1}, all Si rates (2.1, 4.2, 6.3, and 8.4 mg Si/10 plants) showed an increase in plant height compared to the control (0.0 mg Si/10 plants) (Table 2). Numerically, under salinity concentration of 2.74 dSm^{-1}, plant height significantly increased from 95.1 to 108.2 cm under Si rate of 0.0 and 6.3 mg Si/10 plants, respectively. Similarly, within salinity concentration of 10.74 dSm^{-1}, it significantly increased from 84.3 to 91.2 cm under Si rates of 0.0 and 6.3 mg Si/10 plants, respectively. Generally, Si rate of 6.3 mg Si/10 plants showed the best results of plant height compared to all other Si rates under all salinity concentrations. In contrast, both 0.0 and 8.4 mg Si/10 plants showed the lowest plant height.

Salinity stress precludes plant growth and declines biomass and grain yield of wheat. Our results indicated significant decreases in biomass and grain yield by increasing salinity concentration (Figures 1 and 2). For example, biomass under Si rate of 0.0 mg Si/10 plants significantly decreased by 37% when salinity concentration

Table 2. Plant growth characteristics and chemical compositions of wheat grown under salt stress conditions and treated with Si. Within each level of Si we compare least squares means corresponding to the salinity levels. Significant differences are indicated using different lower case letters down the column. Within each level of salinity we compare least squares means corresponding to the Si levels. Significant differences are indicated using different upper case letters across the row. Significance is determined at a 0.05 level where p-values are adjusted for multiple comparisons.

Properties	Salinity	Silicon application rate (mg Si/ 10 plants)				
	(dSm^{-1})	0.0	2.1	4.2	6.3	8.4
Plant height (cm)	2.74	95.1^{aC}	97.1^{aC}	100.3^{aB}	108.2^{aA}	95.5^{aC}
	5.96	90.4^{bB}	94.2^{bA}	95.5^{bA}	95.6^{bA}	93.8^{abA}
	8.85	88.2^{bB}	92.7^{bA}	93.6^{bA}	94.6^{bA}	92.9^{bA}
	10.74	84.3^{cB}	89.1^{cA}	90.5^{cA}	91.2^{cA}	89.5^{cA}
	13.38	74.3^{dD}	82.1^{dC}	87.4^{dAB}	88.1^{dA}	85.4^{dB}
Chlorophyll a (mg g^{-1})	2.74	1.29^{aC}	1.51^{aB}	1.69^{aB}	1.76^{aA}	1.51^{aB}
	5.96	1.20^{abC}	1.28^{bC}	1.38^{bBC}	1.61^{abA}	1.43^{abAB}
	8.85	1.18^{abB}	1.23^{bB}	1.30^{bAB}	1.43^{bcA}	1.28^{bAB}
	10.74	1.09^{bB}	1.14^{bB}	1.23^{bAB}	1.35^{cA}	1.23^{bAB}
	13.38	1.01^{bC}	1.13^{bBC}	1.21^{bAB}	1.30^{cAB}	1.35^{abA}
Chlorophyll b (mg g^{-1})	2.74	0.70^{aD}	0.75^{aC}	0.79^{aB}	0.85^{aA}	0.74^{aC}
	5.96	0.65^{abC}	0.69^{abBC}	0.74^{abB}	0.77^{bcA}	0.69^{abBC}
	8.85	0.61^{bcD}	0.67^{bBC}	0.70^{bABC}	0.74^{cA}	0.66^{bC}
	10.74	0.57^{cC}	0.61^{cBC}	0.64^{cdAB}	0.67^{dA}	0.61^{cBC}
	13.38	0.42^{dC}	0.51^{dB}	0.59^{dAB}	0.62^{dA}	0.55^{dB}
Carotenoids (mg g^{-1})	2.74	0.56^{aE}	0.62^{aD}	0.65^{aBC}	0.67^{aA}	0.63^{aCD}
	5.96	0.53^{bD}	0.56^{bCD}	0.58^{bBC}	0.62^{bA}	0.54^{bD}
	8.85	0.48^{cD}	0.51^{cC}	0.55^{cB}	0.58^{cdA}	0.51^{cC}
	10.74	0.44^{dD}	0.47^{dC}	0.51^{dB}	0.55^{dA}	0.47^{dC}
	13.38	0.39^{eD}	0.45^{dC}	0.46^{eB}	0.51^{eA}	0.44^{eC}
Proline (µmol g^{-1})	2.74	11.5^{eA}	11.3^{eAB}	10.2^{eC}	8.4^{eD}	7.6^{eE}
	5.96	14.1^{dA}	12.8^{dB}	11.5^{dC}	10.8^{dD}	9.9^{dE}
	8.85	16.7^{cA}	15.6^{cB}	13.8^{cC}	13.2^{cC}	11.4^{cD}
	10.74	17.3^{bA}	16.5^{abcB}	14.9^{abcC}	14.6^{abcC}	12.2^{abD}
	13.38	21.5^{aA}	$20.4a^{B}$	$19.1a^{C}$	18.2^{aD}	16.4^{aE}

increased from 2.74 to 13.38 dSm^{-1}. Similarly, under the Si rate of 6.3 mg Si/10 plants, it significantly decreased by 27% when salinity concentration increased from 2.74 to 13.38 dSm^{-1}. Similar to our results, Tuna et al. (2008) found a decrease in wheat biomass of 39 and 54% in two wheat cultivars when exposed to salinity stress. On the other hand, within each salinity concentration, applied Si alleviated salinity stress and increased wheat biomass and grain yield. For example, under salinity concentration of 2.74 dSm^{-1}, biomass and grain yield significantly increased from 2.21 to 3.06 and from 0.88 to 1.42 g $plant^{-1}$ under Si rates of 0.0 and 6.3 mg Si/10 plants, respectively (Figures 1 and 2). Similarly, under salinity stress of 13.38 dSm^{-1}, biomass and grain yield significantly increased from 1.39 to 2.09 and from 0.62 to 0.83 g $plant^{-1}$ under Si rates of 0.0 and 6.3 mg Si/10 plants, respectively. Liang (1999) found an increase in biomass and grain yield when applied Si to barley (*Hordeum vulgare* L.) plants grown under salinity stress. Also, Ahmad (2014) found an increase in biomass and grain yield in wheat grown under salt stress and fertilized by K-silicate. Generally, the highest biomass and grain yield were observed under the lowest salinity concentration of 2.74 dSm^{-1} and under Si rate of 6.3 mg Si/10 plants, but the lowest biomass and grain yield were observed under the highest salinity concentration of 13.38 dSm^{-1} with no Si application (0.0 mg Si/10 plants). It is important to notice that applying Si to soils with higher salt concentration could produce higher biomass and grain yield compared to the soils with no salt stress. For example, applying Si of 6.3 mg Si/10 plants to the soil with salinity concentration of 10.74 dSm^{-1}, produced

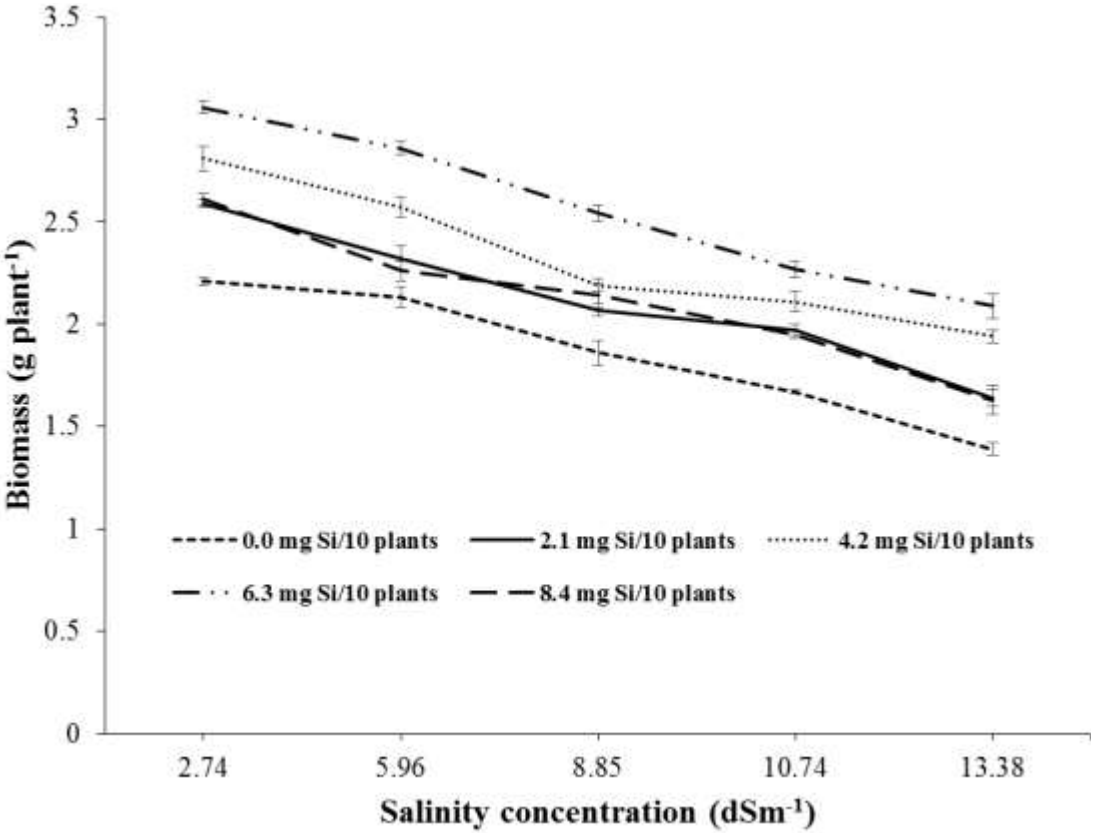

Figure 1. Impact of Si application on wheat biomass yield under different levels of salinity stress. Error bars represent standard error.

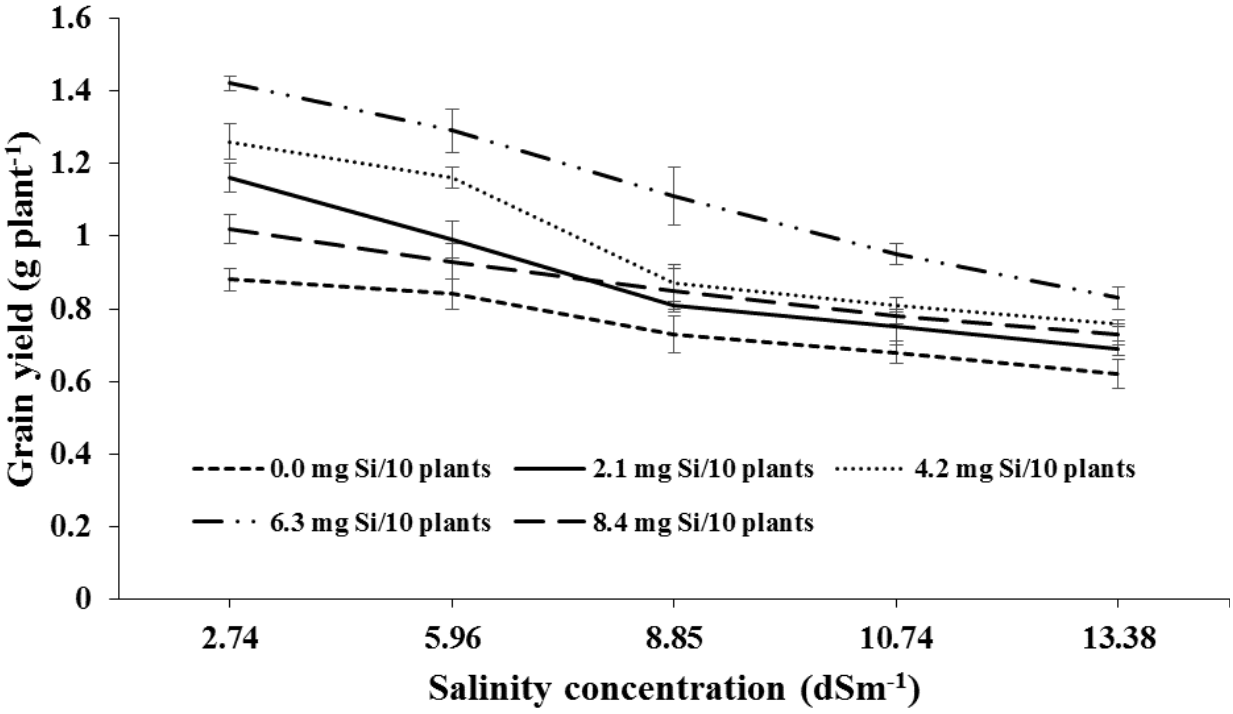

Figure 2. Impact of Si application on wheat's grain yield under salinity stress conditions. Error bars represent standard error.

Table 3. Nutrients concentrations in wheat straw under K-silicate fertilizer and salt stress conditions. Within each level of Si we compare least squares means corresponding to the salinity levels. Significant differences are indicated using different lower case letters down the column. Within each level of salinity we compare least squares means corresponding to the Si levels. Significant differences are indicated using different upper case letters across the row. Significance is determined at a 0.05 level where p-values are adjusted for multiple comparisons.

Nutrient	Salinity	Silicon application rate (mg Si/ 10 plants)				
	(dSm^{-1})	0.0	2.1	4.2	6.3	8.4
N (g kg^{-1})	2.74	13.1^{aD}	14.2^{aC}	15.5^{aB}	17.7^{aA}	13.3^{aD}
	5.96	12.3^{bD}	13.8^{aC}	14.5^{bBC}	16.3^{bA}	12.8^{abD}
	8.85	11.7^{bD}	12.9^{bC}	13.7^{cB}	15.3^{cA}	12.1^{cdD}
	10.74	10.3^{cD}	12.0^{cC}	13.4^{cB}	14.4^{dA}	11.5^{dC}
	13.38	08.5^{dD}	09.5^{dC}	11.9^{dB}	12.9^{eA}	09.5^{eC}
P (g kg^{-1})	2.74	2.7^{aD}	3.1^{aC}	3.5^{aB}	4.1^{aA}	3.1^{aC}
	5.96	2.4^{bD}	2.6^{bBCD}	2.8^{bB}	3.2^{bA}	2.6^{bBCD}
	8.85	2.0^{cD}	2.5^{bC}	2.7^{bABC}	2.9^{cdA}	2.5^{bC}
	10.74	1.7^{dD}	2.0^{cC}	2.4^{cdB}	2.7^{dA}	2.1^{cBC}
	13.38	1.1^{eE}	1.6^{dD}	2.1^{dB}	2.4^{eA}	1.6^{dCD}
K (g kg^{-1})	2.74	15.6^{aD}	16.7^{aC}	18.0^{aB}	20.2^{aA}	15.8^{aD}
	5.96	14.8^{bD}	16.3^{aC}	17.1^{bBC}	18.8^{bA}	15.3^{abD}
	8.85	14.4^{bD}	15.4^{bC}	16.2^{cB}	17.8^{cA}	14.5^{cdD}
	10.74	12.8^{cD}	14.5^{cC}	15.9^{cB}	16.8^{dA}	13.9^{dC}
	13.38	11.1^{dD}	12.1^{dC}	14.4^{dB}	15.4^{eA}	12.1^{eC}
N uptake (mg $plant^{-1}$)	2.74	17.4^{aE}	20.4^{aC}	24.1^{aB}	29.1^{aA}	18.9^{aC}
	5.96	15.7^{bD}	18.3^{bC}	20.5^{bB}	24.8^{bA}	17.7^{abC}
	8.85	13.1^{cD}	16.2^{cC}	18.1^{cdB}	22.1^{cA}	15.5^{cC}
	10.74	10.2^{dE}	14.6^{dCD}	17.3^{dB}	19.3^{dA}	13.7^{dD}
	13.38	6.4^{eD}	9.11^{eC}	14.1^{eB}	16.2^{eA}	9.10^{eC}
P uptake (mg $plant^{-1}$)	2.74	3.56^{aD}	4.44^{aC}	5.47^{aB}	6.72^{aA}	4.27^{aC}
	5.96	3.08^{bD}	3.49^{bcC}	3.99^{bB}	4.80^{bA}	3.54^{bcC}
	8.85	2.36^{cD}	3.24^{cC}	3.53^{cBC}	4.17^{cA}	3.22^{cC}
	10.74	1.68^{dD}	2.43^{bC}	3.07^{dB}	3.59^{dA}	2.59^{dC}
	13.38	0.81^{eD}	1.49^{eC}	2.52^{eB}	3.03^{eA}	1.68^{eC}
K uptake (mg $plant^{-1}$)	2.74	20.8^{aE}	23.9^{aC}	27.9^{aB}	33.1^{aA}	22.4^{aD}
	5.96	18.9^{bD}	21.6^{bC}	24.1^{bB}	28.6^{bA}	21.1^{abC}
	8.85	15.9^{cD}	19.4^{cC}	21.4^{cdB}	25.6^{cA}	18.7^{cC}
	10.74	12.7^{dD}	17.6^{dC}	20.5^{dB}	22.7^{dA}	16.6^{dC}
	13.38	8.6^{eD}	11.5^{eC}	16.9^{eB}	19.4^{eA}	11.4^{eC}

a higher biomass of 2.27 g $plant^{-1}$ compared to that of 2.13 g $plant^{-1}$ produced from the soil with no salt stress (2.74 dSm^{-1}) that did not receive Si application (0.0 mg Si/10 plants) (Figures 1 and 2).

Nutrient concentrations and their uptake in wheat straw

Salinity stress precluded plants to take up nutrients (e.g., N, P, and K), which was reflected in decreasing their concentrations in plants' shoots (mixture of stems and leaves), grains, and their uptake from soils. Results in Table 3 showed significant decrease in N, P, and K concentrations in wheat's straw under each individual Si application while increasing salinity concentration. For example, concentrations of N, P, and K, under the Si rate of 0.0 mg Si/10 plants, significantly decreased as salinity concentration increased from 2.74 to 13.38 dSm^{-1}. Similarly, under the Si rate of 4.2 mg Si/10 plants, N, P,

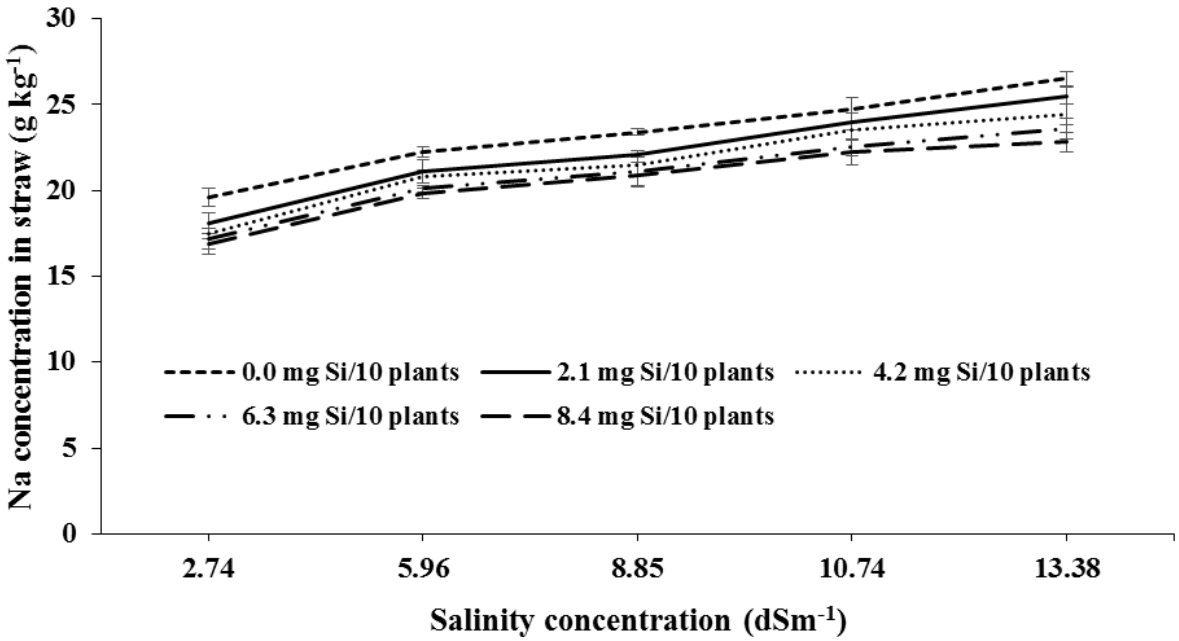

Figure 3. Impact of Si application on Na concentration in wheat's straw under salinity stress. Error bars represent standard error.

and K concentrations in straw significantly decreased when salinity concentration increased from 2.74 to 13.38 dSm^{-1} (Table 3). However, supplying Si to wheat ameliorated salinity stress and increased the concentrations of these nutrients (N, P, and K) in straw within each individual salinity concentration. For example, within salinity concentration of 2.74 dSm^{-1}, concentrations of N, P, and K significantly increased when Si rate increased from 0.0 to 6.3 mg Si/10 plants (Table 3). Similarly, under salinity concentration of 8.85 dSm^{-1}, N, P, and K concentrations significantly increased when Si rate increased from 0.0 to 6.3 mg Si/10 plants. In their review article, 2Rizwan et al. (2015) reported several results of increasing the concentrations of N, P, and K in wheat straw when wheat was fertilized by Si.

Similar to the trend of N, P, and K concentrations in wheat straw, their total uptake significantly decreased within each individual Si rate with increasing salinity concentration. For example, the uptake of N, P, and K in wheat straw, within the Si rates of 0.0 and 8.4 mg Si/10 plants, significantly decreased as salinity concentrations increased from 2.74 to 13.38 dSm^{-1} (Table 3). Results of Table 3, however, revealed an increase in the uptake of N, P, and K when supplying Si to all salinity concentrations. For example, N, P, and K uptake in wheat straw, within salinity concentrations of 2.74 and 10.74 dSm^{-1}, significantly increased when Si rate increased from 0.0 to 6.3 mg Si/10 plants.

In saline soils that have high concentration of Na, plants take up Na in higher amounts than their needs. In our work, Na concentration in wheat straw increased with increasing salinity concentrations. Within the Si rates of 0.0 and 8.4 mg Si/10 plants, Na concentration significantly increased in wheat straw when salinity concentration increased from 2.74 to 13.38 dSm^{-1} (Figure 3). Similar to our results, Saqib et al. (2008) in their work on alleviating salinity stress on wheat by supplying Si found an increase in Na concentration in wheat straw with increasing salinity concentration. However, applied Si resulted in declining Na concentration in straw of wheat grown under salinity stress. For example, within salinity concentrations of 2.74 and 13.38 dSm^{-1}, Na concentration in straw significantly decreased when the applied Si rate increased from 0.0 to 8.4 mg Si/10 plants (Figure 3). Under salinity stress, deposition of Si in plant roots precluded the bypass of Na^+, which resulted in decreasing Na^+ concentration in plant tissues (Zhang and Shi, 2013). Furthermore, an x-ray analysis of rice (*Oryza sativa* L.) grown under salinity stress conditions showed that Si deposition in the roots reduced Na^+ uptake and transfer via the apoplastic pathway (Gong et al., 2006).

Silicon concentration in wheat straw decreased with increasing salinity stress (Figure 4). Within the Si rates of 0.0 and 8.4 mg Si/10 plants, Si concentration in straw significantly decreased when salinity concentration increased from 2.74 to 13.38 dSm^{-1}. However, applied Si to wheat ameliorated salinity stress and increased Si concentration in wheat straw. For example, within salinity concentrations of 2.74 and 13.38 dSm^{-1}, Si concentration significantly increased when applied Si rate increased from 0.0 to 8.4 mg Si/10 plants (Figure 4). Similarly, Tuna et al. (2008), and Saqib et al. (2008) found a decrease in

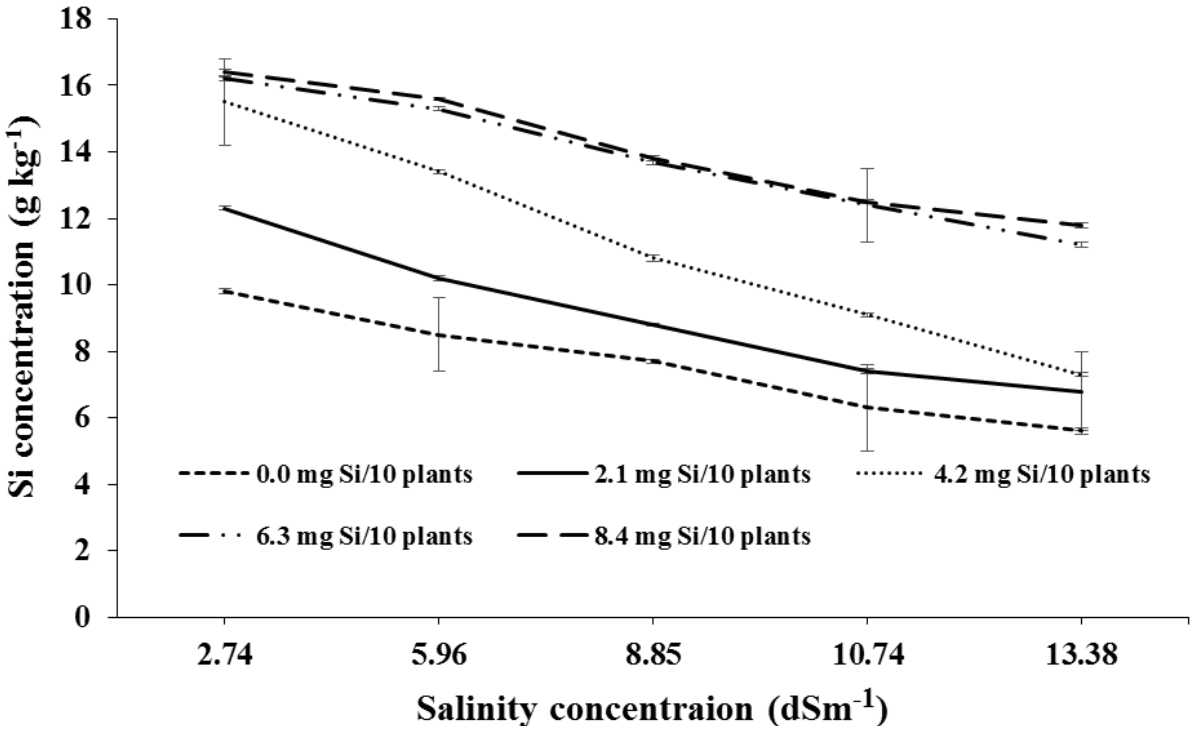

Figure 4. Impact of Si application on Si concentration in wheat's straw under salinity stress. Error bars represent standard error.

Si concentration with increasing salinity and an increase in its concentration with increasing the applied Si rates.

Nutrient concentrations and their uptake in wheat grains

Concentrations of N, P, K, and their uptake in wheat grains were also affected by salinity and Si application. Data in Table 4 revealed significant decrease in N, P, and K concentrations and their uptake under each individual Si rate by increasing salinity concentration. For example, N, P, and K concentrations under the Si rate of 0.0 mg Si/10 plants, significantly decreased when salinity concentration increased from 2.74 to 13.38 dSm^{-1} (Table 4). Under the same previous Si rate, the uptake of N, P, and K significantly decreased when salinity concentration increased from 2.74 to 13.38 dSm^{-1}. Similarly, the three nutrients N, P, and K concentrations and their uptake under the applied Si rate of 6.3 mg Si/10 plants, significantly decreased when salinity concentration increased from 2.74 to 13.38 dSm^{-1}. However, applying Si to wheat increased the concentrations of N, P, K, and their uptake in wheat grains under all of the salinity concentrations. Results in Table 4 showed that concentrations of N, P, K, and their uptake under salinity concentration of 2.74 dSm^{-1}, significantly increased when the applied Si rate increased from 0.0 to 6.3 mg Si/10 plants. Similarly, Rizwan et al. (2015) found an increase in N, P, and K concentrations in the grains of wheat grown under salt stress when applying Si. Under salinity concentration of 8.85 dSm^{-1}, N, P, and K concentrations significantly increased when applied Si rate increased from 0.0 to 6.3 mg Si/10 plants (Table 4). Similarly, under the aforementioned salinity concentration, the uptake of N, P, and K, in wheat grains, significantly increased when the applied Si rate increased from 0.0 to 6.3 mg Si/10 plants.

Conclusions

Salinity stress decreased wheat growth, photosynthetic pigments content, nutrient (N, P, and K) concentrations and their uptake, biomass, and grain yield. In contrast, Na and proline concentrations in wheat increased with increasing salinity concentrations. Applying Si to wheat ameliorated salinity stress and increased biomass, grain yield, nutrient concentrations (N, P, and K) and their uptake, and decreased Na and proline concentrations. Further, Si application increased Si concentration in wheat straw and it was proportional to the increase in applied Si. Generally, the best results of all of the growth characteristics and nutrient concentrations and their uptakes were obtained from the Si rate of 6.3 mg Si/10 plants under salinity level of 2.74 dSm^{-1}. Conversely, the

Table 4. Nutrients concentrations in wheat grains under K-silicate fertilizer and salt stress conditions. Within each level of Si we compare least squares means corresponding to the salinity levels. Significant differences are indicated using different lower case letters down the column. Within each level of salinity we compare least squares means corresponding to the Si levels. Significant differences are indicated using different upper case letters across the row. Significance is determined at a 0.05 level where p-values are adjusted for multiple comparisons.

Nutrient	Salinity	Silicon application rate (mg Si/ 10 plants)				
	(dSm^{-1})	0.0	2.1	4.2	6.3	8.4
N (g kg^{-1})	2.74	13.6^{aD}	14.7^{aC}	16.1^{aB}	18.2^{aA}	13.8^{aD}
	5.96	12.8^{bD}	14.3^{aC}	15.2^{bBC}	16.8^{bA}	13.3^{abD}
	8.85	12.3^{bD}	13.3^{bC}	15.2^{bB}	15.8^{cA}	12.5^{cdD}
	10.74	10.8^{cD}	12.4^{cC}	13.8^{cB}	14.9^{dA}	11.9^{dC}
	13.38	08.9^{dD}	10.1^{dC}	12.4^{dB}	13.4^{eA}	10.1^{eC}
P (g kg^{-1})	2.74	3.7^{aD}	4.1^{aC}	4.5^{aB}	5.1^{aA}	4.2^{aC}
	5.96	3.4^{bD}	3.6^{bCD}	3.8^{bBC}	4.2^{bA}	3.7^{bCD}
	8.85	3.1^{cD}	3.5^{bBC}	3.8^{bABC}	3.9^{cdA}	3.5^{bC}
	10.74	2.6^{dD}	3.0^{cC}	3.4^{cdBC}	3.6^{dA}	3.1^{cC}
	13.38	2.0^{eE}	2.5^{dD}	3.0^{dB}	3.4^{eA}	2.7^{dCD}
K (g kg^{-1})	2.74	11.3^{aD}	12.4^{aC}	13.7^{aB}	15.9^{aA}	11.5^{aD}
	5.96	10.5^{bD}	12.0^{aC}	12.5^{bcBC}	14.5^{bA}	11.0^{abD}
	8.85	09.8^{bD}	11.1^{bC}	12.6^{bcB}	13.5^{cA}	10.3^{cdD}
	10.74	08.5^{cD}	10.2^{cC}	11.6^{cB}	12.6^{dA}	09.6^{dC}
	13.38	06.7^{dD}	07.7^{dC}	10.1^{dB}	11.1^{eA}	07.7^{eC}
N upt^{a}ke (mg pl^{a}nt^{-1})	2.74	11.9^{aD}	17.1^{aC}	20.3^{aB}	25.7^{aA}	16.3^{aC}
	5.96	10.7^{abD}	14.3^{bC}	17.4^{bB}	21.8^{bA}	11.7^{bcD}
	8.85	8.93^{cdD}	10.7^{cdBC}	12.4^{cdB}	17.5^{cdA}	10.6^{cdC}
	10.74	7.48^{dD}	9.4^{dC}	11.2^{dB}	14.3^{dA}	9.10^{dC}
	13.38	5.52^{eD}	6.9^{eCD}	9.40^{eB}	11.2^{eA}	6.81^{eCD}
P upt^{a}ke (mg pl^{a}nt^{-1})	2.74	3.23^{aD}	4.76^{aC}	5.72^{aB}	7.23^{aA}	4.73^{aC}
	5.96	2.86^{abD}	3.62^{bC}	4.43^{bB}	5.40^{bA}	3.13^{bD}
	8.85	2.28^{cdD}	2.87^{cC}	4.43^{bABC}	4.31^{cA}	2.96^{bC}
	10.74	1.86^{dD}	2.25^{dCD}	2.72^{deB}	3.52^{dA}	2.41^{cdBC}
	13.38	1.25^{eD}	1.76^{eC}	2.38^{eB}	2.82^{eA}	1.88^{dC}
K upt^{a}ke (mg pl^{a}nt^{-1})	2.74	9.91^{aE}	14.4^{aCD}	17.4^{aB}	22.5^{aA}	13.6^{aD}
	5.96	8.82^{abD}	12.1^{bC}	14.7^{bB}	18.8^{bA}	9.70^{bcD}
	8.85	7.29^{cdD}	8.90^{cdC}	11.7^{cdB}	14.9^{cA}	8.62^{cdCD}
	10.74	5.89^{dD}	7.72^{dC}	9.30^{dB}	12.1^{dA}	7.41^{dC}
	13.38	4.11^{eD}	5.29^{eCD}	7.71^{eB}	9.20^{eA}	5.33^{eCD}

lowest values were observed under salinity concentration of 13.38 dSm^{-1} without Si application (0.0 mg Si/10 plants).

Conflict of Interests

The authors have not declared any conflict of interests.

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