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Journal of Plant Nutrition

ISSN: 0190-4167 (Print) 1532-4087 (Online) Journal homepage: http://www.tandfonline.com/loi/lpla20

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To cite this article: Munir Ahmad, Mohamed H. El-Saeid, Muhammad Abrar Akram, H. R. Ahmad, Haseeb Haroon & Abid Hussain (2016) Silicon fertilization – A tool to boost up drought tolerance in wheat (Triticum aestivum L.) crop for better yield, Journal of Plant Nutrition, 39:9, 1283-1291, DOI: 10.1080/01904167.2015.1105262

To link to this article: http://dx.doi.org/10.1080/01904167.2015.1105262

Accepted author version posted online: 09 Nov 2015.
Published online: 09 Nov 2015.

JOURNAL OF PLANT NUTRITION
2016, VOL. 39, NO. 9, 1283–1291
http://dx.doi.org/10.1080/01904167.2015.1105262

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Silicon fertilization – A tool to boost up drought tolerance in wheat (*Triticum aestivum* L.) crop for better yield

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ABSTRACT
In this study, impact of silicon (Si) application on wheat performance under drought stress is studied. Experimental soil was sandy clay loam with an average pH of 8.01, electrical conductivity (EC) of 2.36 dSm^{-1}, and calcium carbonate ($CaCO_3$) content of 2.16%. Soil was severely deficient in organic matter (<1%). Average extractable phosphorus (P) and potassium (K) concentration was 230 and 5.21 mg kg^{-1}, respectively. Silicon potassium metasilicate (K_2SiO_3) was applied at the rate of 0 and 12 kg/ha with three canal water irrigation frequencies including two, three, and four under randomized complete block design (RCBD) factorial fashion with three replications. Results indicated that drought stress significantly reduced plant height, spike length, shoot fresh weight, and number of spikelets/spike, eventually enhancing wheat yield. Concentration of K^+ in shoot (28.65 mg g^{-1}) and grains (3.51 mg g^{-1}) increased with Si application, which helped to maintain water potential in plant even under reduced moisture level in plants and soil, ultimately producing more yield and biomass under drought stress conditions.

ARTICLE HISTORY
Received 27 February 2014
Accepted 28 July 2014

KEYWORDS
Wheat; silicon; drought stress; yield; K^+ concentration

Introduction

The demand of food is increasing day by day with rapidly growing world population. Water scarcity among natural limiting factors has significant impact on food production in arid regions. Declining water resources, reprehensible mean annual rainfall distribution, and mismanagement of water resources have a negative impact on crop production. It is estimated that in 2050 we need to feed 9.1 billion people with the ever-decreasing land resources (Hubert et al., 2010). Water is among the most limiting resources around the world and it is decreasing as a result of climate change. It is a challenge for researchers to increase crop production by using limited resources to decrease yield gap under water stress conditions. Water scarcity is a most critical factor responsible for yield reduction of food crops along with nutrient deficiency, late sowing, weeds, and imbalance fertilization (Araus et al., 2002; Khan et al., 2010). Drought is a prominent issue in arid and semiarid regions with low annual rainfall and increased evapotranspiration rate (Ellsworth, 1999; Samarakoon and Gifford, 1995). Water deficiency even for a short period of time can badly influence growth and development of plants resulting in reduced yield (Ashraf and Mehmood, 1990; Kashiwagi et al., 2013). Plants have adopted some alterations to cope up with the drought by inducing physiological and morphological changes (Sakamoto and Murata, 2002). Among these alterations, accumulation of low-molecular-weight organic metabolites is of prime importance as it maintains turgor pressure within the cell and prevents the cells from

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injury under dehydration conditions (Bohnert and Jensen, 1996; Bohnert et al., 1995). This phenomenon helps to stabilize the structure and functioning of certain macromolecules (Santoro et al., 1992). Increasing water use efficiency (WUE) in plants under drought conditions is a key to improve crop production. Several artificial means to intensify drought tolerance have been introduced in plants through genetic engineering (Waseem et al., 2011). Exogenous application of certain nutrients helps plant to overcome stress problems such as drought, salinity, and other biotic as well as abiotic stresses. Broadcasting in soil and foliar application of silicon (Si) has gained importance as it reduces drought stress. Si constitutes about 10% of plant dry matter, but still it is not considered as an essential element (Sacala, 2009). It is taken as H_4SiO_4 (monosilicic acid) by the plants and it maintains water balance of plants, keeping the leaves and xylem vessels functional under drought conditions (Hattori et al., 2005). Its application improves dry matter yield of wheat crop under drought stress (Gong et al., 2003). Formation of silica–cuticle double layer on leaves limits the stomatal opening and enhances water potential in leaves under Si application (Matoh et al., 1991). It also promotes water transport and root development under water stress conditions. Si application improved leaf water status by decreasing excess transpiration through modification of stomatal conductance and reduction in cuticle transpiration in rice plants (Hattori et al., 2005; Matoh et al., 1991). Si also reduces the transpiration rate in maize and increases WUE through modification of root hydraulic resistance (Gao et al., 2004). It also promotes plant growth by changing endogenous growth hormones production (Hamayun et al., 2010).

Wheat (*Triticum aestivum* L.) is a staple food in many parts of the world, but its production is not enough to meet the demand. Water shortage inhibits cell expansion and reduces biomass production (Ashraf and Mehmood, 1990). It has also altered different metabolic and enzymatic activities of plants (Ashraf and Naqvi, 1995; Ashraf and O'Leary, 1996; Lawlore and Cormic, 2002). Drought can create ionic imbalance (Kidambi et al., 1990) and interrupt solute accumulation (Khan et al., 1999).

Water stress has reduced crop yield regardless of the growth stage (Jensen and Mogensen, 1984). Wheat is also a staple food in Pakistan; despite all the efforts made so far, the national average yield per acre is still far less than the research stations and progressive farms.

In Pakistan, very few works report on the use of Si to ameliorate water stress in wheat, particularly under field conditions (Ahmad et al., 2007). Keeping in view the above facts, this study was planned to evaluate the role of Si fertilization in improving wheat crop production and water balance in crop through analyzing K^+ concentration in plants

Materials and methods

Soil sampling and analysis

The experiment was conducted during winter season 2011–2012. Surface soil samples (0–15 cm) were collected from an experimental area. The samples were dried, ground, and sieved with a 2-mm sieve. Soil samples were analyzed for physiochemical characteristics prior to field trail (Table 1). The soil in the site was sandy clay loam in texture with average pH of 8.01, lime content of 2.16%, and electrical conductivity (EC_e) of 2.36 dS m^{-1}. The site was severely deficient in organic matter. Extractable potassium (K) and phosphorus (P) were found to be 230 and 5.20 mg kg^{-1}, respectively. Average Si concentration extracted with 0.01 M calcium carbonate was 29.45 mg kg^{-1} ranging between 25.63 and 34.32 mg kg^{-1}.

Field experiment

Six treatments were used in different plots. Area taken for every plot was 20 m^2. Treatment were included with two levels of Si (0 and 12 kg ha^{-1}) and three levels of irrigation (2, 3, and 4 irrigations) and arranged in randomized complete block design (RCBD) factorial fashion with three replications. A promising wheat variety Sehar-2006 was sown using hand drill at 50 kg ha^{-1} seed rate. The recommended dose of nitrogen, phosphorus, and potassium (NPK) (85:80:40 kg ha^{-1}) was applied. All P and K were applied at the time of sowing, while N was applied in three equal splits: first with P and

Table 1. Physicochemical characteristics of the soil (0–15 cm) collected from the experimental field.

Physicochemical parameters	Mean ± SD	Range
[z]Soil pH	8.01 ± 1.23	7.12–8.91
[z]Soil EC (dS m^{-1})	2.36 ± 2.12	1.19–6.98
[y]Organic Matter %	0.65 ± 0.19	0.23–0.96
[x]Lime contents%	2.16 ± 1.98	1.33–7.17
[w]Sand %	58.2 ± 13.2	31.36–66.51
Silt %	17.8 ± 3.83	9.16–26.98
Clay %	24 ± 5.23	11.71–32.56
Soil textural class	Sandy clay loam	
[z]Extractable K^+ (mg kg^{-1})	230 ± 10.71	181–248
[v]Olsen P (mg kg^{-1})	5.20 ± 1.82	3.14–6.32
[u]$CaCl_2$ extracted Si (mg kg^{-1})	29.45 ± 4.58	25.63–34.32

[z]Richard, 1954 [y]Nelson and Sommers, 1982 [x]Allison and Moodie, 1965 [w]Bouyoucos, 1962 [v]Olsen and Sommers, 1982 [u]Haysom and Chapman, 1975.

K, second with first irrigation and third with third irrigation. Si was applied at the rate of 12 kg ha^{-1} at the time of sowing in the form of potassium silicate (K_2SiO_3). Canal water was applied to irrigate the crop through flooding irrigation system at crown root initiation, tillering, booting, and panicle initiation stages. Wheat crop was harvested at maturity and agronomic parameters were recorded. Shoot and grain samples were collected in separate paper bags and labeled accordingly. Sun-dried samples were oven dried at 65°C up to a constant weight. Samples were finely ground with the help of Wiley mill (IKA Werke, Germany) fitted with stainless steel chamber and blades. Wet digestion procedure (Jones and Case, 1990) was used for determination of K^+ concentration in shoot and grains of wheat samples using flame photometry techniques.

Statistical analysis

Data collected during the study were statistically analyzed using computer-based software, Microsoft Excel and Statistix 8.1® (Steel and Torrie, 1980). Least significant difference (LSD) test was used for separating significantly different treatment means (Little and Hills, 1978).

Results and discussion

Plant growth parameters

All the treatments were statistically significant. The significant ($p < 0.05$) interactive influence of irrigation frequency and Si applications was observed. Treatments having four irrigations had more plant height, shoot fresh weight, spike length, number of spikelets/spike, and number of fertile tillers followed by the treatments with three irrigations (Table 2a). Si application at the rate of 12 kg ha^{-1} significantly increased shoot fresh weight, spike length, number of spikelets/spike, and plant height compared with the treatments without Si fertilization (Table 2b). Si combined with four irrigations gave maximum shoot fresh weight (12.76 t ha^{-1}), plant height (91.25 cm), spike length (12.25 cm), and number of fertile tillers/m^2 (515.33) and spikelets/spike (16.70) (Table 2c). It was noticed that growth parameters increased with increase in irrigation frequency. Similarly, there was a significant difference among the treatment with and without Si application. The trend was different in case of plant height. Treatments with two irrigations combined with Si application gave the same plant height as that of the treatments with three irrigations without Si application. Similarly, treatment with four irrigations without Si had statistically the same plant height as treatment with three irrigations combined with Si. Si fertilization increased shoot fresh weight, fertile tillers/m^2, plant height, spikelets/spike, and spike length up to 18%, 27%, 5%, 6% and 9% compared with the treatments without Si.

Table 2. Mean and range values showing individual and interactive effect of irrigation frequencies and silicon fertilization on various growth parameters of wheat grown in field.

Effect of irrigation frequencies

No. of Irrigations	Shoot fresh wt. (t ha^{-1})	Fertile tillers (m^{-2})	Plant height (cm)	Spikelets/spike	Spike length (cm)
4	$12.25^a \pm 0.56$	$459.33^a \pm 61.55$	$98.13^a \pm 0.48$	$17.18^a \pm 0.59$	$11.24^a \pm 0.04$
3	$8.96^b \pm 0.29$	$379.67^b \pm 29.34$	$88.88^b \pm 0.71$	$13.33^b \pm 0.55$	$9.39^b \pm 0.04$
2	$7.00^c \pm 0.36$	$338.33^c \pm 15.59$	$81.65^c \pm 0.31$	$11.87^c \pm 0.38$	$7.24^c \pm 0.05$
LSD	0.067	4.73	0.47	0.19	0.06

Effect of silicon fertilization

Si levels (kg Si/ha)	Shoot fresh wt. (t ha^{-1})	Fertile tillers (m^{-2})	Plant height (cm)	Spikelets/spike	Spike length (cm)
12	$10.77^a \pm 1.54$	$428.00^a \pm 68.27$	$92.27^a \pm 1.56$	$16.58^a \pm 1.11$	$11.88^a \pm 0.89$
0	$9.04^b \pm 1.35$	$363.56^b \pm 31.20$	$88.18^b \pm 1.66$	$13.68^b \pm 0.94$	$9.29^b \pm 0.85$
LSD	0.05	3.87	0.38	0.16	0.047

Interactive influence of irrigation and Si fertilization

Irrigations + Si (kg/ha)	Shoot fresh wt. (t ha^{-1})	Fertile tillers(m^{-2})	Plant height (cm)	Spikelets/spike	Spike length (cm)
4+1	$12.76^a \pm 0.05$	$515.33^a \pm 3.51$	$91.25^a \pm 0.72$	$16.70^a \pm 0.26$	$12.25^a \pm 0.05$
4+0	$10.74^b \pm 0.08$	$403.33^b \pm 7.02$	$87.17^b \pm 0.25$	$15.67^b \pm 0.12$	$11.23^b \pm 0.05$
3+1	$9.22^c \pm 0.04$	$406.33^b \pm 2.52$	$87.83^b \pm 0.87$	$15.83^b \pm 0.06$	$10.40^c \pm 0.03$
3+0	$8.70^d \pm 0.05$	$353.00^d \pm 3.60$	$83.90^c \pm 0.70$	$14.83^c \pm 0.06$	$10.37^c \pm 0.05$
2+1	$8.33^e \pm 0.06$	$362.33^c \pm 3.21$	$83.81^c \pm 0.31$	$14.20^d \pm 0.10$	$9.20^d \pm 0.03$
2+0	$7.68^f \pm 0.05$	$334.33^e \pm 3.05$	$81.47^d \pm 0.20$	$13.53^e \pm 0.15$	$8.27^e \pm 0.04$
LSD	0.09	6.70	0.66	0.27	0.08

LSD value at $p < 0.05$. Means with similar superscript letters show statistically nonsignificant results at 0.05 probability.

Epstein (1999) reported that Si application improved plant physiology resulting in more plant growth. It improved growth of many plant species particularly under various abiotic and biotic stresses such as drought and salinity stress (Liang et al., 2003; Ma, 2004), because it mainly improved plant water status by alleviating the midday depression in leaf water potential by preventing excessive transpiration through stomatal apertures, resulting in higher dry matter production (Gong et al., 2006; Matoh et al., 1991; Romero-Aranda et al., 2006). Si fertilization increased plant growth and development in normal as well as stress conditions depending upon plant species and dose applied (Agurie et al., 1992; Ali et al., 2009; Hossain et al., 2002; Ma, 2004; Matichenkov et al., 2001; Rodrigues et al., 2003). It also increased plant height, number of tillers, and spike length as Si helped plant to keep its leaves and stem more vigorous, thus reducing self-shading and increasing photosynthesis rate (Agarie et al., 1993; Salman et al., 2012; Yoshida et al., 1962). Enhanced photosynthesis rate with Si application ultimately increased vegetative growth of the plant (Liang et al., 1994).

Yield parameters

Si application increased biological, grain, and straw yield of wheat significantly ($p < 0.05$) at all irrigation levels (Figure 1). Maximum grain yield was observed with Si application at four irrigations (4.38 t/ha), which was 35% more compared to the treatment with Si application at two irrigations (3.25). It shows that irrigation frequency had significant effect on grain yield. Maximum increase in grain yield (25%) was observed when three irrigations were combined with Si and minimum increase in grain yield (13.4%) was observed at four irrigations with Si compared with treatments having the same number of irrigations without Si application. Si application increased straw yield up to 12.3% more than the control when two irrigations were applied. Increased grain and straw yields with Si application might be due to reduction in transpiration rate and improvement in photosynthetic rates (Adatia and Besford, 1986; Liang, 1999), which was related with leaf ultra-structure, chlorophyll content, and ribulose bisphosphate carboxylase activity (Mercedes et al., 2006). Similar results were reported by Epstein

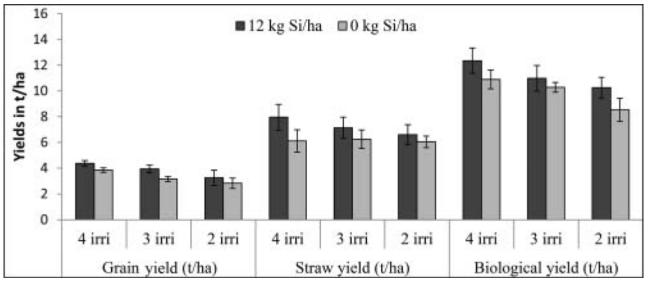

Figure 1. Grain, straw, and biological yield of wheat in t/ha under different numbers of irrigations with and without Si fertilization.

(1999) and Adatia and Besford (1986). They observed grain and straw yield increased in barley and cucumber when fertilized with Si. Liang (1999) reported that Si fertilization increased grain yield of soybean under salt and drought stress.

Harvest index (%)

Si fertilization increased harvest index (HI) of wheat at all irrigation frequencies (Figure 2). Si application and irrigation frequency had a significant ($p < 0.05$) effect HI. Maximum increase in HI (5.8% more) with Si application was observed at two irrigations (lowest water application) and minimum increase was observed at four irrigations (highest water application).

Ali (2009) reported that higher HI value improved the physiological appearance and dry matter production in wheat. Dry matter production increase was more pronounced in response to Si application in wheat (Tahir et al., 2006). Similar results were confirmed in rice cultivars (Ando et al., 1999) and sorghum (Hattori et al., 2005).

Silicon effect in maintaining water potential in wheat plants

Si application and irrigation frequency had significant effects on shoot K+ concentration; however, the interactive effect between Si application and irrigation frequency was non-significant (Figure 3). Maximum increase in K^+ (14.4% >) with Si application was observed at lowest water application (two irrigations), and minimum increase (8.8% >) was observed at four irrigations compared with treatments having no Si. In the current study, K^+ concentration increased when 12 kg/ha Si was applied. Similar results were found by Tahir et al. (2006) and Ahmad et al. (2007).

This was attributed to Si-induced reduction in transpiration rate (Matoh et al., 1986) and to the partial blockage of the transpirational bypass flow (Yeo et al., 1999). In wheat plants, the increased uptake and transport of K^+ from roots to shoots has been thought to be attributable to Si-induced stimulation of the

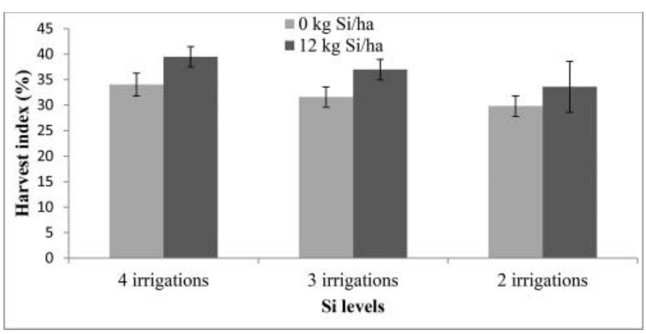

Figure 2. Harvest index (%) of wheat under different numbers of irrigations with and without Si fertilization.

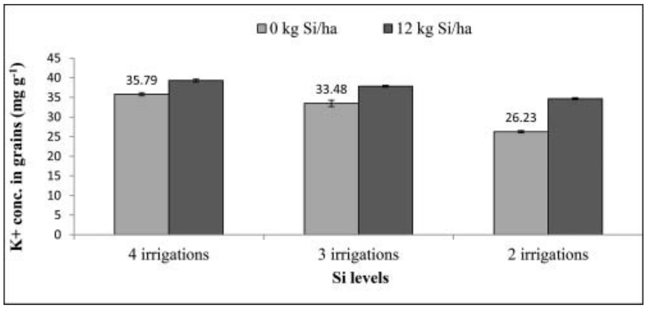

Figure 3. K^+ concentration in shoot (mg g^{-1}) of wheat under different numbers of irrigations with and without Si fertilization.

root plasma membrane H-ATPase under water stress conditions (Liang and Ding, 2002; Liang et al., 1999, 2005, 2006). Addition of Si decreased the permeability of the plasma membrane of leaf cells (Liang, 1999) and significantly improved the ultra-structure of chloroplasts (Liang, 1999). Si application increased grain K^+ concentration at all irrigation frequencies (Figure 4). Maximum increase (13.2%) with Si application was observed at four irrigations, and minimum increase (10.1%) was observed when medium water was applied (two irrigations) as compared to the treatments without Si application.

Plant potassium level decides the survival of plants under water stress conditions, as it is the mineral element that ameliorates the impacts of soil water stress. Potassium enhances the root development and expansion for efficient water absorption from soil (Saxena, 1985). It also decreases transpiration by controlling stomatal opening, thereby saving plant moisture contents (Umar and Moinuddin, 2002). More K^+-containing plants develop sufficient rooting system for more nutrient and water uptake from soil. Under water deficit conditions, K^+ nutrition increases crop tolerance to water stress (Rao, 1986). Drought conditions promote the synthesis of reactive oxygen species (ROS) such as hydrogen peroxide (H_2O_2) and hydroxide (OH^-) in plants. These species are a major limitation in the growth and development of plants due to cellular malfunctioning. ROS are produced during activation of nicotinamide adenine dinucleotide phosphate (NADPH) oxidases and photosynthetic electron transport. With increase in plant potassium status, activity of NADPH oxidases decreases, which hinders ROS production. Sufficient K^+ level decreases NADPH oxidation eight times compared with low K^+ plants; therefore, K^+ status in plants helps in the survival of the plants under drought stress (Cakmak, 2005). The results of present research are in agreement with the results of Liang (1999), who concluded that K^+ concentration increased with Si application in barley grains under salt stress. Potassium concentration in grains of cowpea and kidney bean plants increased through Si addition (Murillo-Amador, 2007). Si maintains higher uptake and accumulation of K^+, thus ensuring drought tolerance under water stress conditions in wheat (Ahmad et al., 1992; Tahir et al., 2006).

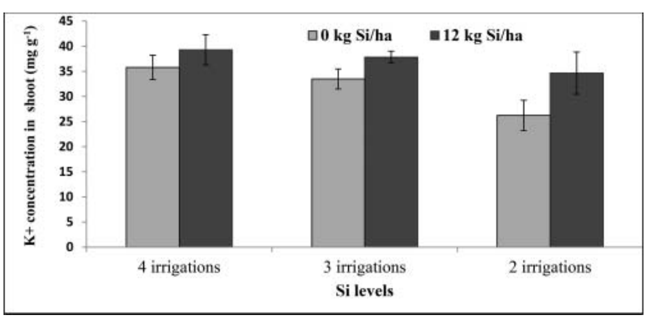

Figure 4. K^+ concentration in grains (mg g^{-1}) of wheat under different numbers of irrigations with and without Si fertilization.

Conclusion

Si is still not considered as an essential mineral element for crops, but it helps the plant to complete its life cycle successfully. Si fertilization to wheat crop significantly increased plant height, and biomass, grain, straw, and biological yield under drought stress conditions. Its application also increased the level of K^+ concentration in shoot and grains of wheat, which maintained the water potential in plants under water deficiency. Si incorporation in general fertilization practices could increase wheat crop production significantly under drought stress conditions.

Funding

This research was supported by the Research Center, College of Food and Agricultural Sciences, Deanship of Scientific Research, King Saud University, Riyadh, Saudi Arabia.

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