

## Mitigating water stress on wheat through foliar application of silicon

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### Abstract

Climate change emerges in different forms such as drought, which is prevalent all over the world, especially in semi-arid and arid regions. Crop production especially wheat (*Triticum aestivum* L.) yield is affected due to water shortage at critical growth stages in Pakistan. A greenhouse experiment was conducted by using plastic trays to assess the performance of wheat to exogenous silicon (Si) application under water stress which in applied through skipping irrigation at critical stages at College of Agriculture, University of Sargodha, Pakistan. Experiment include irrigation levels (I<sub>1</sub>: irrigation at crown root stage + booting stage, I<sub>2</sub>: irrigation at crown root stage + anthesis stage, I<sub>3</sub>: crown root stage + grain development stage, I<sub>4</sub>: crown root stage + booting stage + anthesis stage + grain development stage, I<sub>5</sub>: crown root stage + tillering stage + booting stage + earing stage + milking stage + dough stage) and foliar application of Si viz., Si<sub>0</sub>: 0% (Control), Si<sub>1</sub>: 0.25%, Si<sub>2</sub>: 0.50%, and Si<sub>3</sub>: 1% (w/v). Treatment combination I<sub>1</sub> + Si<sub>0</sub> significantly reduced yield and yield attributes, net assimilation rate, Si contents in plants, leaf water potential, chlorophyll content, root length and water use efficiency furthermore, increased evapotranspiration efficiency. In contrast, treatment combination I<sub>5</sub> + Si<sub>3</sub> significantly increased these parameters and reduced evapotranspiration efficiency. Moreover, treatment combinations I<sub>4</sub> + Si<sub>3</sub> and I<sub>3</sub> + Si<sub>3</sub> were statistically at par with treatment combination I<sub>5</sub> + Si<sub>3</sub> which indicating the role of Si in mitigating negative impact of water shortage and improved these parameters. It is concluded that plant exhibited positive response at irrigation levels I<sub>3</sub> and I<sub>4</sub> in combination with foliar-applied Si<sub>3</sub> while irrigation level lower than I<sub>3</sub> with Si<sub>3</sub> was not showed positive improvement in crop productivity.

**Keywords:** Net assimilation rate, Silicon, Water stress, Water use efficiency, Relative water content

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## Introduction

Wheat has a leading role in human nutrition and animal feed in the world with the largest harvested area (220.1 million hectares) and the second largest production (749.5 million tons) among cereals. In Pakistan, area under wheat cultivation is 8.7 million hectares which gives 25.4 million tonnes grain production and its contribution in value addition and gross domestic product is 9.1 and 1.7% respectively (Economic Survey of Pakistan, 2018). The 22% people of Pakistan are suffering from food shortage due to insufficient wheat production. There are several reasons which restrict the wheat production. However, in recent scenario, climate change has been emerged as a big threat for wheat production in the world (FAO, 2011d). Abnormality in environment like unpredictable and low rainfall especially at maturity and temperature severity at tillering and milking stage resulted in abiotic stress for wheat production. Drought stress along with salinity is two main threats that have reduced about 20% arable land of the world and especially Pakistan (Munns and Tester, 2008). It has been reported that more than 40% yield fluctuation of wheat can be attributed to climate change (heat waves and drought) at the global, national, and subnational scales (Zampieri et al., 2017). The worldwide climate change is creating a series of problems that are disturbing the crop production and has also affected the 58% population which is engaged directly and indirectly related to agriculture (Anonymous, 2012).

Water stress at critical growth stage is the major hindrance for plant growth and development in different climatic conditions (Wang et al., 2014). Wheat is not equally susceptible to water stress during life but some stages like flowering and grain development are severely affected the crop which ultimately causes in yield reduction (Bukhat, 2005; Sinclair, 2011). Water stress at initial critical growth stages like crown root incitation and tillering caused rapid inhibition of roots and shoot which are further leads to stomatal closure resulting in reduction of transpiration rate and CO<sub>2</sub> assimilates during photosynthesis (Neumann, 2008). Results from different studies concluded that water stress during flowering stage mainly affected grain number related traits whereas water stress during flowering impacted grain weight. This is consistent with other studies on wheat, where drought during stem extension caused floret and whole spikelet death and drought during

grain filling reduced grain size and weight (Oosterhuis and Cartwright, 1983; Dorion et al., 1996; Ji et al., 2010; Pradhan et al., 2012). Water stress at anthesis stage caused reduction in pollination process that ultimately reduced the number of grains (Showemimo and Olarewaju, 2007). Anther development and pollen production are particularly sensitive to abiotic stresses such as heat, leading to severe reductions in crop yield (Hedhly et al., 2009). Drought during grain filling stage influences the partitioning of assimilate and enzymes activation that involved in starch and sucrose production (Sinclair, 2011) and also disturb the nutrients uptake and accumulation in wheat (Hattori et al., 2005). Water stress and high temperature are the exclusive cause that damages the female reproductive organs which leads to losses of fertility and production. Therefore, pollen sterility is not the major determinant of fertility loss under high temperature and water scarcity (Fábián et al., 2019). In wheat, higher temperature and water stress collectively reduced 66% to 93% rate of photosynthetic compared with non-stress conditions. Moreover, water stress at intermediate or suboptimal condition increased 24% water use efficiency (WUE), moreover, high temperature decreased 34% WUE (Hassan, 2006; Prasad et al., 2011). Sufficient supply of water at anthesis stage enhances the photosynthetic rate and also provides additional period for carbohydrate translocation towards grains which increases the size of grains (Zhang and Oweis, 1999). Crop yield improvement depends upon the water accessibility at following stages i.e. booting, flowering, grain filling and milking stage (Ashraf and Harris, 2004). Water scarcity at later stages causes decrease in grain weight and number (Gupta et al., 2001). Chlorophyll contents are enhanced during vegetative stage under unlimited water supply (Lawson and Blatt, 2014). Water stress during early vegetative growth affects different phenological stages like stem elongation, leaf area, and tillering, maybe by declined CO<sub>2</sub> assimilation in the leaf and slow nutrient mobilization to developing tissues due to lower stomatal conductance, transpiration rate and low relative water content (Barnabas et al. 2008; Lipiec et al. 2013).

Silicon (Si) availability to wheat usually low due to its immobility in plants (Hattori et al., 2005) and its accumulation depends on crop species and crop growth stages (Mecfel et al., 2007). Moreover, most of the researcher concluded that Si lower the risk of diseases, improve photosynthetic rate and grain production in cereals under water stress (Shashidhar



et al., 2008). In vegetative growth, Si seems non-essential while its application in stress condition improves the growth of family Gramineae especially wheat. Plant structural study has exposed that its recommended amount is essential for cell differentiation and development (Liang et al., 2005). Wheat crop is also known as Si accumulator that is useful for development under abiotic and biotic (diseases and insect) stresses (Liang et al., 2003). However, under favourable condition its functions are minimum (Epstein, 2009; Gong et al., 2005). Application of Si on the foliage of plant under drought develops tolerance in wheat through improving the plant water use efficiency by reduction transpiration from plants surface (Gao et al., 2006). Foliar-applied Si at tillering and anthesis enhances biomass and grain yield, respectively (Al-aghaby et al., 2005). Exogenous application of Si at rate of 0.40-0.50% enhanced about 50% grain yield under water stress (Harter and Barros, 2011). Plant tissue analysis showed that Si-induced tolerance against water stress through improvement in antioxidant defence system, which diminished the oxidative stress on cell metabolites (Gong and Chen, 2012). In the light of all above studies, it was speculated that exogenous silicon application could reduce the inauspicious effects of water stress on wheat development and physiological traits. Keeping in view the hypothesis, study was planned to investigate the exogenous application of Si on yield and physiological traits of wheat cultivar *Punjab-2011* under planned water stress condition.

## Material and Methods

### Experimental site and soil

Role of Si levels on yield and physiological traits of wheat (CV. *Punjab-2011*) under water stress which imposed by combinations of irrigation scheduling was studied in a greenhouse experiment at College of Agriculture, University of Sargodha, Pakistan, during 2016-17 under semi-arid (32.08°N latitude, 72.67°E longitude) climate of the Punjab, Pakistan. Soil used was sandy clay loam having physico-chemical characteristics given in Table 1. Greenhouse temperature and humidity was maintained in the range between 26°C to 30°C and 60% to 65% at noontime respectively.

**Table-1: Physico-chemical properties of soil used in the study**

Soil properties	Values		Analytical method used
	Pre-sowing	Post-harvest	
<b>Mechanical composition</b>			Bouycous hydrometer Method (Piper, 1966)
Sand (g kg <sup>-1</sup> )	470 ± 3.1		
Silt (g kg <sup>-1</sup> )	240 ± 2.3		
Clay (g kg <sup>-1</sup> )	290 ± 1.6		
Textural class	Sandy clay loam		
<b>Chemical composition</b>			Method 27a, US Salinity Laboratory Staff, 1954
Saturation percentage	39.20 ± 1.20	41.73 ± 1.15	
pH	7.73 ± 0.03	7.70 ± 0.05	Beckman's Glass electrode pH meter (Jackson, 1973)
ECe (µS cm <sup>-1</sup> )	16.39 ± 24.1	18.79 ± 29.78	Conductivity bridge from 1:2:5 soil water ratio
Soil organic matter (g kg <sup>-1</sup> )	8.43 ± 0.68	8.59 ± 0.39	Walkyey and Black method (Piper, 1966)
Total soil N (mg kg <sup>-1</sup> )	4.12 ± 9.17	4.20 ± 8.34	Modified Kjeldahl Method (Piper, 1966)
NaHCO <sub>3</sub> Extractable-P (mg kg <sup>-1</sup> soil)	7.59 ± 0.12	8.70 ± 0.29	Olsen's Method (Jackson, 1973)
Available potassium (mg kg <sup>-1</sup> )	267 ± 10.12	269 ± 12.10	Flame photometric (Jackson, 1973)

Values are mean of four replicates followed by (±) standard error of means

### Crop husbandry

Seeds of wheat were sown in plastic trays, each of 27.94 cm width, 54.28 cm length and 35.86 cm depth, each plastic tray was filled with 12 kg soil. The 40 seeds of wheat cultivar --- were sown in each tray. Fertilizer was used as recommended for wheat i.e. 120:100:60 kg ha<sup>-1</sup> N:P:K with urea, DAP and K<sub>2</sub>SO<sub>4</sub>, respectively. Nitrogen was used in three splits in which 1/3<sup>rd</sup> along with whole total phosphorus and potassium fertilizers were incorporated in the soil before sowing. Remaining nitrogen dose was top dressed in two equal splits at tillering and anthesis stage. At the completion of germination, 20 seedlings per trays were maintained and irrigated according to water stress treatments.

### Experimental treatments and design

For treatment allocation, completely randomized design (CRD) with factorial arrangement and having four replications was adopted. Study treatments included water stress at different critical growth stages



viz., I<sub>1</sub>: two irrigations at crown root stage + booting stage, I<sub>2</sub>: two irrigations, crown root stage + anthesis stage, I<sub>3</sub>: two irrigations, at crown root stage + grain development stage, I<sub>4</sub>: four irrigations, crown root stage + booting stage + anthesis stage + grain development stage, I<sub>5</sub>: six irrigations, crown root stage + tillering stage + booting stage + earing stage + milking stage + dough stage); and foliar application of sodium silicate Na<sub>2</sub>Si<sub>3</sub>O<sub>7</sub> solution with different concentrations viz., Si<sub>0</sub>: 0% (Control, water spray with 0 Si), Si<sub>1</sub>: 0.25% (10.86 mg/100 mL water), Si<sub>2</sub>: 0.50% (21.73 mg/100 mL of water), Si<sub>3</sub>: 1% (43.46 mg/100 mL of water). For the formulation of 0.25%, 0.50% and 1% Si solution, 10.86 mg, 21.73 mg and 43.46 mg Na<sub>2</sub>Si<sub>3</sub>O<sub>7</sub> was weighted on electrical weighing balance (BL3200HL Japan) and each was dissolved in to 100 mL of distilled water separately. Exogenous silicon was sprayed at tillering and anthesis stage at the time of sunset to ensure Si uptake by the leaves in two consecutive days.

### Data collection

At physiological maturity, number of productive tillers was counted from 5 plants than their averages were taken. Height of plants was measured by using meter rod. Grains per spike were counted from 5 plants and then their average was calculated. From each experimental unit a sub-sample of 1000-grain was taken and weighted by an analytical balance (Model Number: HC2204) after oven-drying at 70°C for 24 hours in an oven until a constant weight was obtained. At physiological maturity, wheat plants were harvested from each experimental unit, tied up in bundles and tagged accordingly. To determine biological yield of each experimental unit, these bundles were weighed by using bench scale (Model Number: TCS-602). All bundles were threshed separately and grain yield was weighed and converted in Mg (mega gram) per hectare. Silicon concentration in plants was measured at anthesis and grain filling stage. For, Si analysis, harvested plant samples were washed thoroughly with distilled water. For two days, samples were placed in open air then air dried samples were dried at 70°C with the help of air driven oven. After drying, samples were converted into a fine powder through grounding. Digested 0.20 g plant sample through 50% NaOH and 50% H<sub>2</sub>O<sub>2</sub> solution than placed the beakers on hot plate at 150°C for 2h for complete the digestion. Colorimetric molybdenum blue method was used for the estimation of Si from the digested samples (Elliot and Snyder, 1991). Then, take

50 ml volumetric flask and made a solution having 1 ml filtrate liquid, 25 ml acetic acid (20%) and 10 ml of ammonium molybdate. After five minutes add 5 ml tartaric acid (20%) and 1 ml of reducing solution (1 g Na<sub>2</sub>SO<sub>3</sub>, 0.5 g 1 amino-2-naphthol-4-sulfonic acid and 30 g NaHSO<sub>3</sub> in 200 ml water) and 20% citric acid to made the solution up to the volume. Spectrophotometer (Shimadzu, Japan) at 650 nm was used to check the absorbance. Barrs and Weatherly (1962) method was used for the determination of relative water content. For this purpose, weighted fresh leaflets were imbibing into distilled water for four hours in petri plate. After four hours, turgid weight of leaflets was calculated then dried in an oven at 80°C for 48 hours for recording dry weight of leaflets. Following formula was used for calculation of relative water content (RWC):

$$RWC (\%) = \frac{\text{Fresh weight (g)} - \text{Dry weight (g)}}{\text{Turgid weight (g)} - \text{Dry weight (g)}} \times 100 \quad (1)$$

Chlorophyll was measured with chlorophyll meter, model no. (SPAD-502 Plus) between 10:00 AM and 02:00 PM. Each measurement was repeated three times and the average was included for analysis. (Tennant, 1975) method was used for the measurement of root length. For this purpose, randomly selected five plants were dug-out with a sampling tool having 7 cm sharp cutting tip. Then, soil and other residues were carefully separated from the roots through gentle washing. Root length was noted in centimeters from ground level to the root tips. Ehdai and Waines (1994) formulae was used for calculation of water use efficiency and evapotranspiration efficiency (ETE), respectively

$$WUE (kg m^{-3}) = \frac{\text{Grain yield}}{\text{Water used rate}} \quad (2)$$

$$ETE (kg m^{-3}) = \frac{\text{Biological yield}}{\text{Water used rate}} \quad (3)$$

### Statistical analysis

Analysis of variance (ANOVA) techniques was applied on collected data by using the statistical program SAS 9.1 (SAS Institute, 2008) and Duncan's Multiple Range test at P≤0.05 was used for comparison of the means (Steel et al., 1997).

## Results and Discussion

Foliar application of Si has significant effect on wheat yield and yield components under irrigation levels





(Table 2). Irrigation level I<sub>5</sub> showed that full irrigation produced 7% taller wheat plant than irrigation level I<sub>1</sub> (Table 2). Moreover, Si<sub>3</sub> in irrigation level I<sub>5</sub> produced 15% taller plant than Si<sub>0</sub> at I<sub>1</sub> level. Plant height of I<sub>4</sub> and I<sub>3</sub> were statistically similar with I<sub>5</sub> along with Si<sub>3</sub>. Among Si concentrations, Si<sub>3</sub> express 6% taller plant than Si<sub>0</sub> (Table 2). Likewise, Si<sub>3</sub> presented 14% higher productive tillers than Si<sub>0</sub> (Table 2) while I<sub>5</sub> produced 9% more productive tillers than water stress I<sub>1</sub>.

Moreover, Si<sub>3</sub> along with irrigation level I<sub>5</sub> produced 24% higher productive tillers than Si<sub>0</sub> with irrigation level I<sub>1</sub> (Table 2). Number of grains per spike in Si<sub>3</sub> was 8% more than that Si<sub>0</sub> (Table 2). Irrigation level I<sub>5</sub> produced 13% higher grains per spike than irrigation level I<sub>1</sub>. Among irrigation × silicon interactions, I<sub>5</sub> and I<sub>3</sub> in combination with Si<sub>3</sub> produced 18% higher grains per spike than those observed with I<sub>1</sub> × Si<sub>0</sub> interaction.

**Table-2: Irrigation and silicon interaction effect on yield and yield attributes, biological yield, net assimilation rate and silicon contents in plants of semi-arid wheat.**

Irrigation levels	Silicon Conc.	Plant height (cm)	Tiller (m <sup>2</sup> )	Grains per spike	1000-grain weight (g)	Biological yield (Mg ha <sup>-1</sup> )	Grain yield (Mg ha <sup>-1</sup> )	NAR (g m <sup>2</sup> d <sup>-1</sup> )	Si contents (mg g <sup>-1</sup> )	
									Anthesis	Grain
	Si <sub>0</sub> (0)	98.3d <sup>¶</sup>	231d	46.8d	37.7d	8.9d	3.2d	3.6d	4.1d	4.1d
	Si <sub>1</sub> (0.25%)	100.3c	243c	48.1c	40.1c	12.2c	4.3c	4.2c	5.6c	5.2c
	Si <sub>2</sub> (0.50%)	102.6b	258b	49.2b	42.8b	14.1b	5.5b	4.5b	6.1b	6.1b
	Si <sub>3</sub> (1%)	105a	270a	50.6a	44a	15.8a	6.1a	5.1a	6.8a	7.1a
<b>Irrigation levels × Foliar application of silicon</b>										
I <sub>1</sub>	Si <sub>0</sub> (0)	92.8	213	43	34.5	7.3	2.7	3.10	4.0	3.2
	Si <sub>1</sub> (0.25%)	96.6	225	43.1	39	8.7	3.0	3.11	4.3	4.5
	Si <sub>2</sub> (0.50%)	98.2	245	45.1	41.2	10.1	3.2	3.10	4.7	4.7
	Si <sub>3</sub> (1%)	98.5	254	46.2	40.6	10.8	3.9	3.5	4.5	6.0
	Mean	96.5 C <sup>§</sup>	234C	44.3C	38.8C	9.2C	3.2C	3.2C	4.3C	4.6C
I <sub>2</sub>	Si <sub>0</sub> (0)	98.3	231	45.1	38.7	8.1	3.4	3.71	4.1	3.4
	Si <sub>1</sub> (0.25%)	100	236	46.6	39.3	11.7	3.3	3.74	5.1	5.3
	Si <sub>2</sub> (0.50%)	100.5	253	47.2	40.5	13.0	4.3	4.71	5.4	7.0
	Si <sub>3</sub> (1%)	100.6	261	50.8	42.1	14.1	5.6	4.72	6.4	6.0
	Mean	99.8B	245B	47.4B	40.1B	11.7B	4.1B	4.1B	5.2B	5.4B
I <sub>3</sub>	Si <sub>0</sub> (0)	100.3	242	47.7	38.4	9.4	3.2	3.60	4.3	5.1
	Si <sub>1</sub> (0.25%)	101.8	248	51.9	40.2	13.9	4.7	4.90	5.6	5.6
	Si <sub>2</sub> (0.50%)	103.7	261	51.5	43.9	14.7	6.5	5.10	7.5	5.7
	Si <sub>3</sub> (1%)	108.6	274	50.9	46.4	17.8	6.9	5.70	7.8	7.8
	Mean	103.6A	256A	50.5A	42.2A	13.9A	5.3A	4.8A	6.3A	6.1A
I <sub>4</sub>	Si <sub>0</sub> (0)	100.3	227	49.3	38	10.4	3.2	4.1	4.2	4.8
	Si <sub>1</sub> (0.25%)	101	251	48.9	40.7	13.2	5.5	4.7	6.4	5.2
	Si <sub>2</sub> (0.50%)	105.6	272	51.2	44.8	16.5	6.6	4.8	6.1	6.6
	Si <sub>3</sub> (1%)	108.4	279	52.8	45.5	17.6	6.7	5.8	7.8	7.8
	Mean	103.8A	257A	50.5A	42.2A	14.4A	5.5A	4.8A	6.1A	6.1A
I <sub>5</sub>	Si <sub>0</sub> (0)	99.8	242	49	38.9	9.6	3.3	3.8	4.2	4.3
	Si <sub>1</sub> (0.25%)	102.2	253	49.8	41.1	13.8	5.1	4.8	6.7	5.7
	Si <sub>2</sub> (0.50%)	105.1	265	51.3	43.6	16.5	6.9	4.9	6.8	6.7
	Si <sub>3</sub> (1%)	108.9	281	52.6	45.8	18.7	7.2	5.8	7.9	7.9
	Mean	104A	257A	50.6A	42.3A	14.6A	5.6A	4.8A	6.4A	6.2A
DMR P≤ 0.05(I × Si)		5.5	17.1	3.5	3.77	3.2	1.7	0.94	1.48	2.14

<sup>¶</sup>Means separated by lower case letter in each column are not significantly different among foliar application of silicon at P≤0.05.

<sup>§</sup>Means separated by upper case letter in each column are not significantly different among irrigation levels treatments at P≤0.05.

ns = Non-significant; NAR = Net assimilation rate



Regarding 1000-grain weight,  $I_5$  produced 8% more 1000-grain weight than  $I_1$  while  $I_4$  and  $I_3$  were statistically similar with  $I_5$  treatment. In case of Si concentrations,  $Si_3$  produced 14% higher 1000-grain weight than  $Si_0$ . Irrigation  $I_5$  in interaction with 1% Si produced 25% more 1000-grain weight than  $Si_0$  with irrigation level  $I_1$ . Irrigation level  $I_4$  and  $I_3$  with  $Si_0$  showed statistically similar with  $I_5$  with  $Si_3$  (Table 2). Data showed that 37% and 43% higher biological and grain yield in  $I_5$  than  $I_1$  (Table 2). Irrigation levels  $I_4$  and  $I_3$  were statistically similar with  $I_5$ . Exogenous application of 1% Si under irrigation level  $I_5$  produced 61% and 63% higher biological and grain yields, respectively than water stress  $I_1$  along with  $Si_0$ . Among Si concentrations,  $Si_3$  produced 44% and 48% higher biological and grain yield. Irrigation level  $I_4$  and  $I_3$  with  $Si_3$  were statistically similar with  $I_5$  with  $Si_3$  (Table 2). Silicon concentration  $Si_3$  produced 70% more net assimilation rate (NAR) than  $Si_0$  (Table 2). The trend of Si application under irrigation level showed that full irrigation along with 1% Si produced 47% more NAR than irrigation level  $I_1$  along with  $Si_0$ . Moreover, irrigation levels  $I_4$  and  $I_3$  with foliar applied Si 1% were statistically similar with  $I_5$  in  $Si_3$ . Likewise, water stress  $I_5$  produced 33% more NAR than water stress  $I_1$ .

In the present study, foliar applied Si levels at tillering and anthesis stages significantly improved the growth, yield and physiological attributes in wheat when grown under irrigation levels. In water stress, plants enhanced the activities of superoxide dismutase and peroxidase that favoured plant growth and yield (Noman et al., 2015). Water shortage at critical growth stages of wheat significantly declined the crop production through disturbance of nutrients uptake and movement, rate of respiration and photosynthesis (Gupta and Huang, 2014; Cattivelli et al., 2008). Nawaz et al. (2012) described that moisture stress at early growth stage i.e. crown root initiation meaningfully reduced the phenological development due to lack of nutrients uptake which resulted in lower crop production. It is verified by Gupta et al. (2001) that water stress at anthesis and booting stage resulted in lower number of productive tillers due to poor fertilization process. Moreover, productive tillers were positively correlated with grain and biological yield if irrigated at anthesis stage. Consequently, water stress either at reproductive or vegetative stages can affect the physiological maturity by slow growth and development of productive tillers (Dhaka, 2003). It

had been proven that availability of irrigation at each critical growth stage resulted in the healthy development of physiological attributes due to timely release of essential amino acids (Zhang et al., 2017). Silicon enhanced the water uptake in plants through improving osmotic potential and activity of aquaporin (Chen et al., 2011). Root hydraulic conductance showed the water uptake capacity of roots (Steudle, 2000; Hattori et al., 2008). It has been verified by the different studies that negative effect of water stress on crops were reduced by the application of Si (Gong et al., 2005; Hattori et al., 2005). Silicon has remarkable feature in up keeping the relative water contents under water stress (Lux et al., 2002). Iannucci et al. (2002) said that water stress lowered the relative water contents and nutrient uptake in plant body while application of Si on cultivars performed excellent and maintained turgor pressure through which plant growth and yield improved.

Data related to Si concentrations in wheat at anthesis and grain stage as presented in Table 2 revealed that effect of irrigation levels and silicon concentrations imparted significant  $p \leq 0.05$  effect at anthesis and grain formation stage. Among Si treatments, foliar applied Si ( $Si_3$ ) at anthesis and grain formation stages have maximum concentration of Si 40% and 42%, respectively than  $Si_0$ . Foliar applied Si 1% with irrigation level  $I_5$  have 49% and 60% higher Si contents in wheat at anthesis and grain formation stages as compared to  $Si_0$  with  $I_1$ . Irrigation level  $I_5$  showed better (33% at anthesis and 42% at grain formation stage) as compared to  $I_1$  but  $I_4$  and  $I_3$  have maximum Si contents in plants and statistically similar with  $I_5$ . The results also narrated that Si concentration in plants at anthesis and grain formation stage were significantly  $P \leq 0.05$  increased by the application of  $Si_3$  (Table 2). Relative water content (RWC) of leaves as influenced by irrigation levels and foliar applied Si are presented in Table 3. The data on relative water content indicated that  $I_5$  with  $Si_3$  has 20%, 7% and 12% higher RWC over  $I_1$  with  $Si_0$  at 70, 95 and 120 DAS respectively. Significantly  $p \leq 0.05$  8%, 5% and 3% higher RWC were recorded in  $Si_3$  at 70, 95 and 120 DAS than  $Si_0$ . Among irrigation levels,  $I_5$  treatment showed 10%, 4% and 4% higher relative water content than  $I_1$  at 70, 95 and 120 DAS (Table 3). Data of chlorophyll content (SPAD value) indicated that irrigation levels and foliar applied Si (Table 3) had significant  $p \leq 0.05$  effect while their interactive effect was found non-significant at 70, 95 and 120 DAS.



**Table-3: Irrigation and silicon interaction on leaf water and chlorophyll content, root length, water use and evapotranspiration efficiency in plants of semi-arid wheat.**

Irrigation levels	Si Conc.	Leaf Relative water content (%)			Chlorophyll content (SPAD)			Root length (cm)	WUE (kg m <sup>-3</sup> )	ETE (kg m <sup>-3</sup> )
		70 DAS	95 DAS	120 DAS	70 DAS	95 DAS	120 DAS			
	Si <sub>0</sub> (0)	11.1c <sup>ψ</sup>	19.8d	29.5c	28.9c	36.7c	13.7d	29.6b	0.82d	2.38d
	Si <sub>1</sub> (0.25%)	11.2b	20.2c	29.6c	29.9bc	38.2b	15.8c	30.1b	0.89c	2.54c
	Si <sub>2</sub> (0.50%)	11.6b	20.6b	29.8b	30.8b	39.2b	17.4b	31.0b	1.05b	2.76b
	Si <sub>3</sub> (1%)	12.1a	20.9a	30.4a	32.5a	40.8a	19.3a	32.2a	1.57a	3.15a
<b>Irrigation levels × Foliar application of silicon</b>										
I <sub>1</sub>	Si <sub>0</sub> (0)	10.3	19.8	28.0	27.2	36.5	13.2	27.3	0.55	2.37
	Si <sub>1</sub> (0.25%)	10.4	19.2	29.3	28.8	37.1	13.8	28.5	0.66	3.10
	Si <sub>2</sub> (0.50%)	10.8	20.3	29.1	30.0	37.6	16.4	29.0	0.84	3.38
	Si <sub>3</sub> (1%)	11.5	20.4	29.9	30.2	39.7	18.6	31.1	0.92	3.96
	Mean	10.7D <sup>§</sup>	19.9E	29.1D	29.1B	37.7B	15.5	29.0C	0.74E	3.20A
I <sub>2</sub>	Si <sub>0</sub> (0)	11.2	19.7	29.2	29.3	36.6	13.6	28.5	0.76	2.21
	Si <sub>1</sub> (0.25%)	11.1	20.3	29.6	30.0	37.8	14.4	30.2	0.81	3.01
	Si <sub>2</sub> (0.50%)	12.0	20.2	29.6	30.4	38.4	16.3	30.6	0.91	2.03
	Si <sub>3</sub> (1%)	11.9	20.7	30.3	31.1	40.6	19.0	31.3	1.30	3.60
	Mean	11.5C	20.2D	29.7C	30.2A	38.4AB	15.8AB	30.2B	0.95D	2.71B
I <sub>3</sub>	Si <sub>0</sub> (0)	11.0	20.2	28.5	29.4	36.9	13.4	30.7	0.86	3.30
	Si <sub>1</sub> (0.25%)	12.0	20.3	29.6	30.2	38.3	16.7	30.5	0.97	1.20
	Si <sub>2</sub> (0.50%)	11.7	20.3	29.7	30.7	40.4	18.4	31.7	1.03	3.10
	Si <sub>3</sub> (1%)	12.0	20.9	30.9	33.7	40.8	20.1	32.8	1.74	3.02
	Mean	11.7BC	20.5C	29.7C	31.0A	39.1A	17.2AB	31.4A	1.15C	2.66B
I <sub>4</sub>	Si <sub>0</sub> (0)	11.4	19.0	29.7	29.8	36.8	14.4	30.5	0.98	2.00
	Si <sub>1</sub> (0.25%)	11.0	20.2	30.2	30.4	38.8	16.3	30.6	1.03	2.01
	Si <sub>2</sub> (0.50%)	12.0	20.9	30.6	30.9	39.7	18.5	30.8	0.99	3.01
	Si <sub>3</sub> (1%)	12.4	22.0	30.7	33.7	41.0	19.3	32.8	1.89	2.90
	Mean	11.7B	20.5B	30.3B	31.2A	39.1A	17.1AB	31.2A	1.22B	2.48B
I <sub>5</sub>	Si <sub>0</sub> (0)	11.8	20.3	29.0	28.6	36.7	14.1	30.8	0.96	2.01
	Si <sub>1</sub> (0.25%)	11.5	20.2	30.2	30.1	38.9	17.9	30.7	0.99	3.40
	Si <sub>2</sub> (0.50%)	11.3	20.9	30.7	31.6	39.8	17.6	32.9	1.50	2.29
	Si <sub>3</sub> (1%)	12.8	21.3	31.7	33.9	41.9	19.4	32.9	1.98	2.28
	Mean	11.9A	20.7A	30.4A	31.0A	39.3A	17.3A	31.8A	1.36A	2.50B
DMR P ≤ 0.05 I × Si		0.64	0.21	0.53	ns	ns	ns	Ns	0.12	0.48

<sup>ψ</sup>Means separated by lower case letter in each column are not significantly different among foliar application of silicon at P ≤ 0.05.

<sup>§</sup>Means separated by upper case letter in each column are not significantly different among irrigation levels treatments at P ≤ 0.05.

ns = Non-significant; WUE = Water use efficiency; ETE = Evapotranspiration efficiency

Significantly  $p \leq 0.05$  6%, 4% and 10% higher chlorophyll contents were recorded in I<sub>5</sub> at 70, 95 and 120 DAS than I<sub>1</sub>. Among the foliar applied Si, Si<sub>3</sub> treatment showed 12%, 10% and 29% higher chlorophyll contents than Si<sub>0</sub> at 70, 95 and 120 DAS. There was no significant difference among irrigation

levels I<sub>3</sub>, I<sub>4</sub> and I<sub>5</sub> at 70, 95 and 120 DAS regarding chlorophyll contents of wheat flag leaf while I<sub>2</sub> was statistically similar with I<sub>3</sub> and I<sub>4</sub> at 95 and 120 DAS. Data showed that significantly  $p \leq 0.05$  (8%) higher root length was recorded in I<sub>5</sub> than I<sub>1</sub> (Table 3). Moreover, irrigation levels I<sub>4</sub> and I<sub>3</sub> were statistically



similar with I<sub>5</sub> with respect to root length. In case of Si concentrations, Si<sub>3</sub> produced significantly  $p \leq 0.05$  (8%) higher root length than control Si<sub>0</sub> while Si<sub>0</sub> and Si<sub>1</sub> were statistically similar with Si<sub>2</sub>. The interactive effect of irrigation levels and foliar applies Si were found non-significant (Table 3). Significantly (46%) higher (WUE) was recorded in water stress I<sub>5</sub> than I<sub>1</sub> (Table 3). Application of Si<sub>3</sub> under irrigation level I<sub>5</sub> showed 72% more WUE than under I<sub>1</sub> with Si<sub>0</sub>. Moreover, Si<sub>3</sub> showed 48% more WUE than Si<sub>0</sub>. Regarding evapotranspiration efficiency (ETE) of wheat, irrigation level I<sub>5</sub> along with Si<sub>3</sub> showed 42% lower ETE than I<sub>1</sub> along with Si<sub>0</sub> (Table 3). Water stress I<sub>5</sub> showed 22% lower ETE than I<sub>1</sub> while I<sub>5</sub>, I<sub>4</sub>, I<sub>3</sub> and I<sub>2</sub> were statistically similar with each other. Foliar applied Si<sub>3</sub> gave 24% lower ETE than Si<sub>0</sub>.

Above findings showed the significant reduction in chlorophyll content due to stress levels. Chlorophyll content is a significant indicator which showed the plant productivity in terms of biomass production (Wang and Huang, 2004). Roy Deluca (2013) stated that wheat under water stress along with Si application significantly affected photosynthetic rate and root length compared than control. Wheat crop up to 60% and other crops up to 20% were less affected by drought with application of Si that increased the root surface area, volume, activity and total length due to which more water absorbed from soil which improved plant growth (Chen et al., 2011). Studies revealed that Si caused significant enhancement in water use efficiency through stimulating enzymatic, non-enzymatic and anti-oxidative defense systems (Liang et al., 2003; Hattori et al., 2005). Evapotranspiration demands to wheat crop have been increased as a result of evaporation due to minimum and sparse plant population and more area faced to sunlight which resulted in reduction of grain yield and water use efficiency. Optimum level of Si decreased the conductance and transpiration rate for leaf that was associated with plant growth under drought condition but no significant effect was recorded on conductance and transpiration rate from cuticle in plant due to Si supply by causing the Si polymers formation on root (Gao et al., 2006).

## Conclusion

It can be concluded that Si application significantly increased biomass and grain yield of wheat cultivar under different irrigation levels, which was found to

be associated with Si-induced increased relative water content, chlorophyll content, root length and water use efficiency. Therefore, application of Si is an effective way of increasing production of wheat in arid or semi-arid areas.

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### Contribution of Authors

Qamar R: Supervised the experiment and approved the manuscript  
Anjum I: Performed experiment  
Rehman AU: Statistical analysis and manuscript write up  
Safdar ME: Provided experimental inputs  
Javeed HMR: Manuscript write up  
Rehman A: Designed experimental layout  
Ramzan Y: Helped in chemical analysis

