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SILICON FOLIAR APPLICATION IMPROVES WATER STRESS TOLERANCE IN WHEAT (*TRITICUM AESTIVUM* L.) BY MODULATING GROWTH, YIELD AND PHOTOSYNTHETIC ATTRIBUTES

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Abstract

Silicon (Si), being an important fertilizer element, has been found effective in enhancing plant tolerance against biotic and abiotic stresses. Despite many reports regarding miraculous effects of silicon fertilization on plants, the penetration ability and efficacy of silicon containing compounds by foliar application is still a challenging question for the plant scientists. The current study was carried out to investigate the effects of the foliar feeding of various soluble silicon sources on photosynthesis and related attributes of wheat (*Triticum aestivum L.)* under water deficit condition. The results indicated that the plants which are subjected to drought showed 36% reduction in above ground shoot weight, 40% diminution in flag leaf area along with the decrease in 25% of total chlorophyll content and 62% reduction in grain weight. The foliar application of silicon containing compounds have remarkable positive effects on flag leaf gas exchange and related attributes under both normally irrigated and water deficit conditions. The foliar applications of silicon containing compounds such as 0.1*mM* of silicic acid reduced the negative effects of water shortage with increase in leaf area (12%), plant biomass (23%) and grain weight (12%) of wheat as compared to the potassium silicate and sodium silicate. It is concluded from the results of this study that silicic acid is an appropriate form of silicon for foliar application followed by potassium silicate and sodium silicate. Moreover, 0.1 *mM* silicic acid was found to be more effective for enhancing photosynthetic efficiency, biomass and yield of wheat under water deficit environment.

Key words: Biomass, Photosynthesis, Pigment contents, Silicon, Water stress, Wheat.

Introduction

Plant productivity under rapidly changing climatic condition has attained the attention of scientists as the major challenge in agriculture sector (Zahedi *et al.,* 2020). Water deficiency even for a short time can disturb the growth and decrease the productivity of plants by disturbing photosynthesis (Jaleel *et al*., 2009; Zhang *et al*., 2019). The imminent climate changes are alarming to address the shortage of water for the production of cereal crops. It is expected that by 2025, about 65% of the world population will face water scarcity (Nezhadahmadi, 2013). The annual turnover of crop production varies due to fluctuation in availability of irrigation water (Jaleel *et al*., 2007). Moreover, unmanaged continuous exploitation of water resources is adding to this problem worldwide. Therefore, it is need of the hour to effectively utilize every drop of available water for better growth of plants (Nakayama *et al*., 2007).

The plant response towards stress depends on many factors such as, nature of plant species, developmental stage and severity as well as duration of stress (Denby & Gehring, 2005; Zhang *et al*., 2019; Saleem *et al*., 2020a). Limited water availability may destroy the cell structure and inhibit the activity of enzymes that ultimately leads towards the plant's demise (Jaleel *et al*., 2008). Water shortage in plants hinders the key processes of development; cell division and cell enlargement (Waraich *et al*., 2011). Physiological and biochemical activities of plants such as, transpiration, photosynthesis, chlorophyll contents, enzyme activities and ion uptake are also affected by reduced water supply (Farooq *et al*., 2009; Sawatraksa, 2018). Water dearth alters the cellular levels of chlorophylls and carotenoids (Anjum *et al*., 2003a; Farooq *et al*., 2009) affecting the photosynthetic activity of the plants (Massacci *et al*., 2008). Photosynthesis is also affected by alteration in relative water content, water potential and stomatal closure in plants experiencing water shortage (Lawlor & Cornic, 2002; Andrew *et al*., 2008; Farooq *et al*., 2009). The challenging threats of the climatic change, ever increasing drought intensity and duration, reduction in the available resources of ground and surface water along with the gradual increase in temperature are adversely affecting the wheat production globally (Lobell & Gourdji, 2012).

It is well reported that the application of different plant growth regulators can reduce the adverse effects of biotic and abiotic stresses (drought, salinity, temperature alleviation) on crops (Tassi *et al*., 2008; Iqbal *et al*., 2011; Waqas *et al*., 2017). Silicon (Si) is the second most abundant metalloid found in the form of mono-silicic acid and is an essential chemical element in plant biology (required by plants, animals and microorganisms. It is a beneficial element for plants and improves the structural integrity of plants exposed to conditions of environmental stress, most importantly; salt, heavy metals, drought, temperature changes and freezing, pests and disease stresses (Liang *et al*., 2007; Zia *et al*., 2017). The exogenous application of silicon can decrease the rate of transpiration and improves the water use efficiency (WUE) in plants experiencing moisture stress (Gao *et al*., 2004; Saleem *et al*., 2020b,c). Silicon is considered as a quasi-essential element (Epstein, and Bloom 2005) and after oxygen; Silicon is the second most prevalent element in soil with relatively higher concentrations in sandy soil (Noori & McNeilly, 2000; Thilagam, 2014).

Plants cultivated in low-silicon containing soil are often more vulnerable to adverse environmental circumstances than plants produced in silicon-rich soils (Ma, 2004; Bakhat *et al*., 2017). Plants usually take up silicon in the form of silicic acid (H_4SiO_4) (Ma & Takahashi, 2002). The concentration of silicon in plants is species specific (Epstein, 2003; Ma, & Takahashi, 2002) dependent on the existence of transporters and the mode of transit (Sahebi *et al*., 2015; Saleem *et al*., 2019).

Over the recent years, various applications such as crop residues, manure, compost, fertilizers, micronutrients, and biochar are being commonly used, and certain abiotic stress including drought have received considerable attention regarding plant morphology and physiology owing to increasing environmental exposure, which are additionally likely to bear negative impacts on cereal crops including wheat. Therefore, the present research was conducted to investigate (I) the effect of Si application on the growth and biomass (II) photosynthetic pigments under the drought stress. Hence, results from the present study will help improve the understanding behind the mechanism of plant using foliar applications of Si.

Materials and Methods

A field experiment was conducted in randomized complete block design (RCBD) to determine the effects of foliar silicon application on gas exchange characteristics and grain yield of wheat. The wheat genotype "Faisalabad-08" was sown at Ayub Agriculture Research Institute (AARI) Faisalabad under field conditions. The experimental area is divided into plots and the size of each plot was 2.5m in length and 5m in width. Twenty plants from each plot were randomly tagged and sprayed with silicon solutions. No external fertilizer was applied in this study. The two water regimes, normal irrigation, one pre sowing (100 mm water) and three (total 228 mm water) other irrigations at different time intervals were applied to the plants receiving normal (recommended for this area by agricultural department) watering with a total rainfall of 102 mm throughout the growth of crop. No irrigation throughout the crop growth cycle (except rain water, 120 mm) was applied to the plants experience the water deficiency (drought). Three different sources of silicon; sodium silicate, potassium silicate and silicic acid were used for foliar spray. Four treatments i.e., no spray (T1), distilled water 0.0 mM Silicon source, (T2), 0.01 Silicon source (T3) and 0.1 mM Silicon source (T4) from each of the above mentioned sources were applied exogenously at two stages, the tillering and the booting stage. About 500 ml of each solution was applied thrice to the selected plants of each treatment with interval of two days. Tween-20 was used as a surfactant for foliar applications of silicon solution.

Data collection: The data for gas exchange and related attributes was collected at the heading stage of wheat plants. The flag leaf area was calculated using the method of Carleton & Foote (1965). The chlorophyll contents of the flag leaf were determined using method of Davies (1976). The fresh leaves were extracted in 80% of acetone and filtered. The absorbance of each sample was measured with the help of spectrophotometer (Hitachi-U-2001, Japan) at three different wavelengths 480, 645, and 663nm, respectively. The gas exchange characteristics of the wheat plants were recorded using an Infrared Gas Analyzer (CI-340; CID, INC., USA). Flag leaf photosynthesis (*Pn*), stomatal conductance (*C*) and transpiration (*E*) rate were recorded from 10.0 a.m. to 12 p.m. Photosynthetic photon flux density (PPFD) at leaf surface was maximum up to 1711 mol m^{-2} s^{-1}, and ambient CO_2 concentration was 352 mol mol^{-1}. The Barr and Weatherley (1962) method was followed to calculate the flag leaf relative water contents (RWC). The following equation was used to calculate the RWC of flag leaf.

$$\frac{(FW - DW)}{(TW - DW)} \times 100$$

where FW is fresh weight, DW is dry weight and TW is turgid weight

The grain weight was recorded after the final harvest of the crop.

Statistical analysis

The data thus collected was subjected to the statistical analysis using the CoStat computer software (CoStat version 6.2, CoHort Software, 2003, Monterey, CA, USA). The means of each treatment were equated by the least significant difference method (Fisher's LSD) at *p*-value of ≤0.05 level. The data were standardized using means of inverse or logarithmic transformations wherever necessary before using it for Analysis of Variance (ANOVA). The graphs were plotted by using the Microsoft excel 2010.

Results

The exogenous application of Si was improved the above ground fresh weight (Table 1) of the wheat genotype under water stress as compared to plants grown under well watered conditions. Plants grown under water deficit condition showed 36% reduction in above ground fresh weight as compared to the normally irrigated plants (Fig. 1). The application of 0.1 mM silicic acid proved to be more useful in increasing above ground fresh weight under normally irrigated and water deficit environment compared with all other levels and forms of silicon sources used in the study. The exogenous application of 0.1 *mM* silicic acid increased the plant fresh weight up to 15 and 23% under normal irrigation and water deficit soil, compared to the plants which were not treated with foliar application of Si. Application of Si increased plant growth and fresh weight of plants by 13 and 6% when plants receiving 0.01 and 0.1 *mM* potassium silicate, respectively as compared to untreated plants (Fig. 1).

Table 1. Mean square values from analysis of variance (ANOVA) table indicating the impact of silicon foliar application and water deficit environment on wheat.

Source of variation	DF	Fresh weight	Leaf area	Chl a	Chl b	Chl a/b	Total Chl	Carotenoids	Transpiration	Stomatal conductance	Photosynthesis	RWC	Grain weight
Block	2	3.47^{ns}	2.93^{ns}	0.002^{ns}	0.001^{ns}	0.003^{ns}	5.07^{ns}	1.75^{ns}	0.034^{ns}	3.65^{ns}	106.9^{ns}	24.4^{ns}	0.15^{ns}
Si Levels	7	25.87***	26.69***	0.087**	0.050^{ns}	0.026^{ns}	0.24***	6.72^{ns}	0.06^{ns}	7.02***	223.7***	50.8^{ns}	1.50**
Water Stress	1	825.93***	808.52***	0.440***	0.409***	0.078^{ns}	1.69***	6.27**	1.95***	54.80***	591.9***	1121***	214***
lev x str	7	12.64*	15.09*	0.031^{ns}	0.048^{ns}	0.039^{ns}	0.05^{ns}	8.37^{ns}	0.05^{ns}	0.97^{ns}	30.6^{ns}	43.1^{ns}	0.564^{ns}
Error	30	4.65	4.71	0.020	0.022	0.021^{ns}	0.04	6.17	0.05	1.22	42.3	29.8	0.407
Total	47												

The negative effects of water deficit were also evident in leaf area measurement as compared to plants grown under normal irrigated soils (Table 1). The flag leaf area was reduced up to 40% in plants experiencing water shortage as compared to the normally irrigated ones. The application of 0.1 mM sodium silicate was proved to be more effective and showed an overall increase of 8% in flag leaf area of treated plants as compared to the untreated ones. The application of the 0.1*mM* silicic acid exhibited an increase of 12% in flag leaf area of plants as compared to untreated ones under water stress condition (Fig. 2).

The wheat plants subjected to the water deficit condition showed 39, 18 and 25% decrease in the chlorophyll a, b and total chlorophyll contents, respectively as compared to the plant grown in the normal irrigation with water.

The foliar application of 0.1 mM silicic acid exhibited more expedient effects in increasing the chlorophyll contents of the wheat plants grown under both normally irrigated as well as water deficit condition as compared to all other sources and levels of the silicon used in this study. An increase of 49, 9 and 27% was observed in chlorophyll a, b and total chlorophyll contents in normally irrigated wheat plants under application of 0.1 mM silicic acid (Figs. 3, 4, 5). Whereas, under the water deficit soil, exogenously applied 0.1mM silicic acid resulted in 28 and 14 % increase of chlorophyll a and total chlorophyll contents respectively as compared to the plants which were not sprayed by Si (Fig. 3, 5). A significant reduction (14%) in the carotenoids contents of the wheat plants was recorded under water deficient condition as compared to the plants which grown under normal irrigated soil with water (Fig. 6). Overall, the application of the 0.1 mM silicic acid showed highest values for the carotenoids followed by the potassium silicate. Under the well watered soils 17% increase was observed by 0.1 mM of silicic acid application while an increase of 20% was recorded in carotenoids contents of silicic acid treated plants under water deficit condition as compared to the plants which were not treated with the application of Si (Fig. 6).

The net photosynthetic rate of the wheat plants experiencing water shortage was found to be 24% less as compared to the plants which grown under normal irrigated soil with water. The exogenous application of 0.01 mM silicic acid produced the increased values of 46 and 45% in the photosynthetic rate of wheat plants receiving normal irrigation and water deficit environment, respectively as compared to the plants which were not treated with the application of Si (Fig. 7).

The stomatal conductance variations were observed under two water regimes (Table 1). The water deficit caused a 45 % decrease in the stomatal conductance of the stressed plants as compared to plants received normal water for irrigation. Under normal irrigation conditions, the application of the 0.1 mM sodium silicate proved to be more useful source showing 40% increased values in stomatal conductance as compared to all others sources and levels of silicon used in this study. Whereas, under the water deficit condition, 0.1 mM of silicic acid application proved to be more effective showing 47% increased in stomatal conductance as compared to plants which were not sprayed with Si (Fig. 8).

The transpiration rate significantly varied in water stressed plants and the plants which were grown under well irrigated soil. Rate of transpiration in water stressed plants was 26% less than those of grown under adequate watered supply to soil (Fig. 9). The relative water content was 14% less in plants receiving limited water supply than those of well watered plants. The application of 0.01 mM of sodium silicate showed the 7% increased values in the relative water content of the wheat plants grown under well watered soils (Fig. 10).

The grain weight of plants experiencing water stress was less as compared to the ones grown under the sufficient supply of water (Table 1). The grain weight of the water stressed plants exhibited 62% reductions as compared to plants grown under regular water supply in soil. Si applications showed a positive effect on the grain weight of the wheat plants (Table 1). The plants treated with 0.01 mM of the potassium silicate and 0.01 mM silicic acid exhibited 12 and 11% increase in the grain weight of the treated plants as compared to the plants at which Si was not applied. (Fig. 11).

Discussion

Environmental variations due to abiotic stresses, such as drought, heat, cold and salinity, adversely affect and limit agricultural productivity in developing countries including Pakistan (Zahedi *et al.,* 2020). About 33% of the world's agricultural land is facing water imbalance and promoting drought vulnerability, which may drastically decrease the growth and yield of cereal crops (Khadka *et al*., 2020). The results of the present study clearly indicated that the limited water supply caused a significant decreased ($p \leq 0.05$) in gas exchange characteristics and yield related attributes of the wheat plants. The exogenous application of silicon was not only helpful to cope with the negative effects of limited water supply but also equally beneficial under well irrigated soil with water as well (Table 1). As it is evident from the results of current study that silicic acid was the most effective source of silicon foliar application to improve water deficit tolerance in the subjected wheat plants. There are other studies describing that (Sahebi *et al*., 2014) the uptake of the Si in plants is mostly in the form of the silicic acid, despite the presence of many other forms of silicon in the soil. The range of soluble silicic acid beneficial for plants had been reported between 0.1–0.6mM (Epstein, 1999; Liang *et al*., 2007) and that the concentration of Si in grass species is higher than all other nutrients (Liang *et al*., 2007). It was revealed by the results of current study that the 0.1 mM of silicic acid showed more beneficial effects to increase the various characteristics of the wheat plants under normal and water limited conditions indicating the greater solubility and absorption of silicic acid in plants. Some other researchers had also reported the almost similar significant effects of soluble Si on different crops (Fawe *et al*., 2001; Kim *et al*., 2002; Rodrigues *et al*., 2003; Kim *et al*., 2017). In rice, the positive effects of other silicon forms, such as potassium silicate had also been reported (Buck *et al*., 2008.

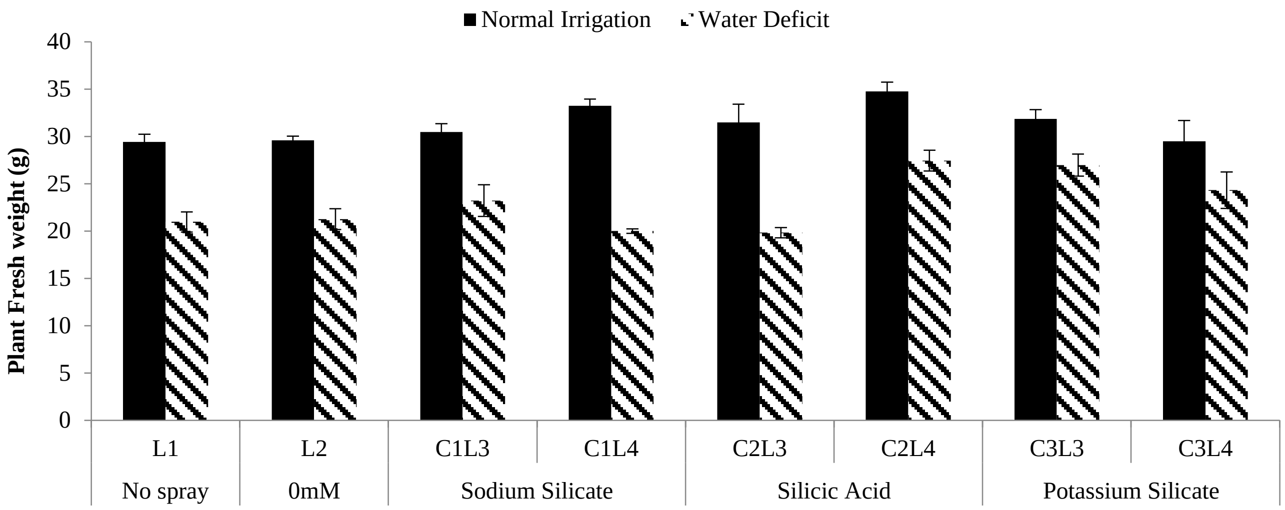

Fig. 1. Influence of different concentrations of silicon on fresh weight (g) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

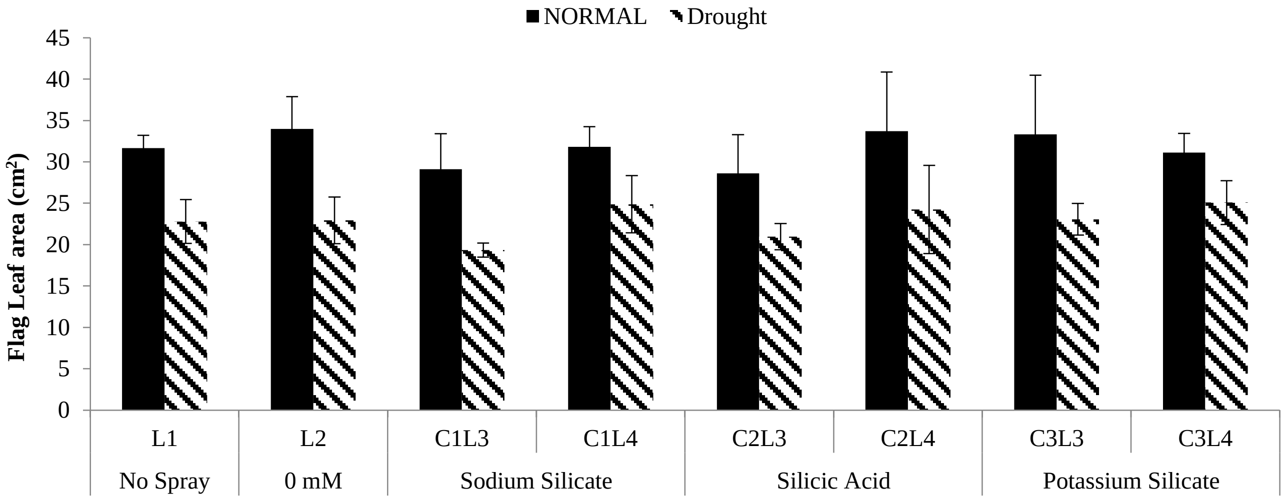

Fig. 2. Influence of different concentrations of silicon on flag leaf area (cm^2) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

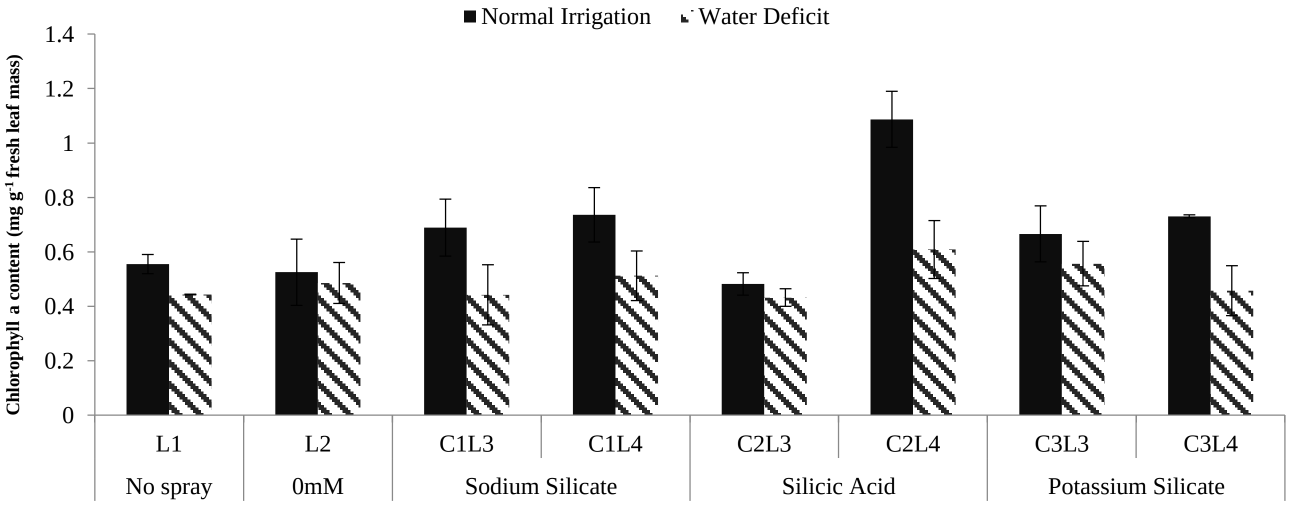

Fig. 3. Influence of different concentrations of silicon on chlorophyll a content (mg g^{-1} fresh leaf mass) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

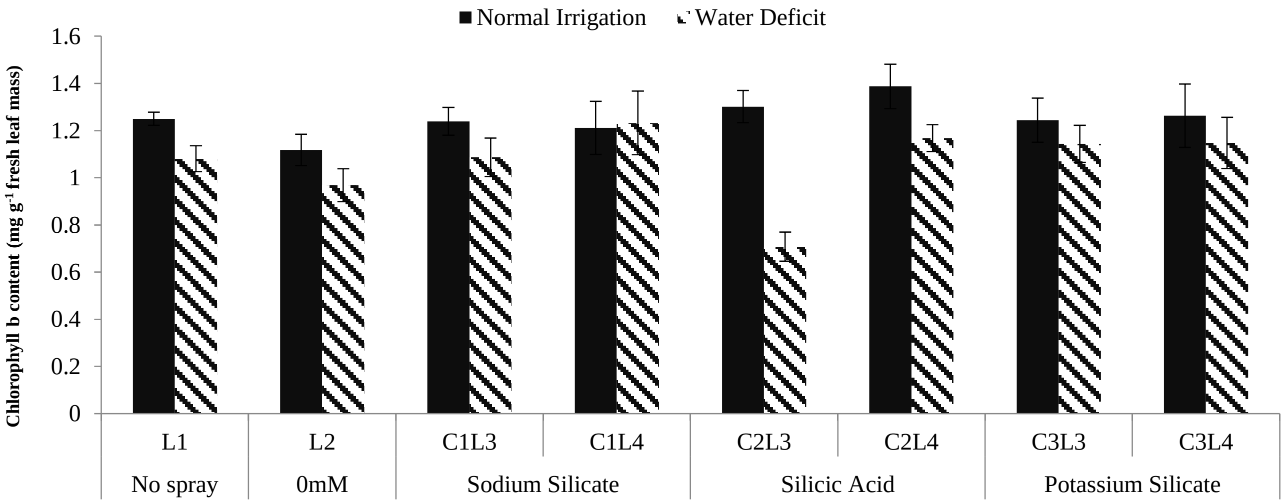

Fig. 4. Influence of different concentrations of silicon on chlorophyll b content (mg g^{-1} fresh leaf mass) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

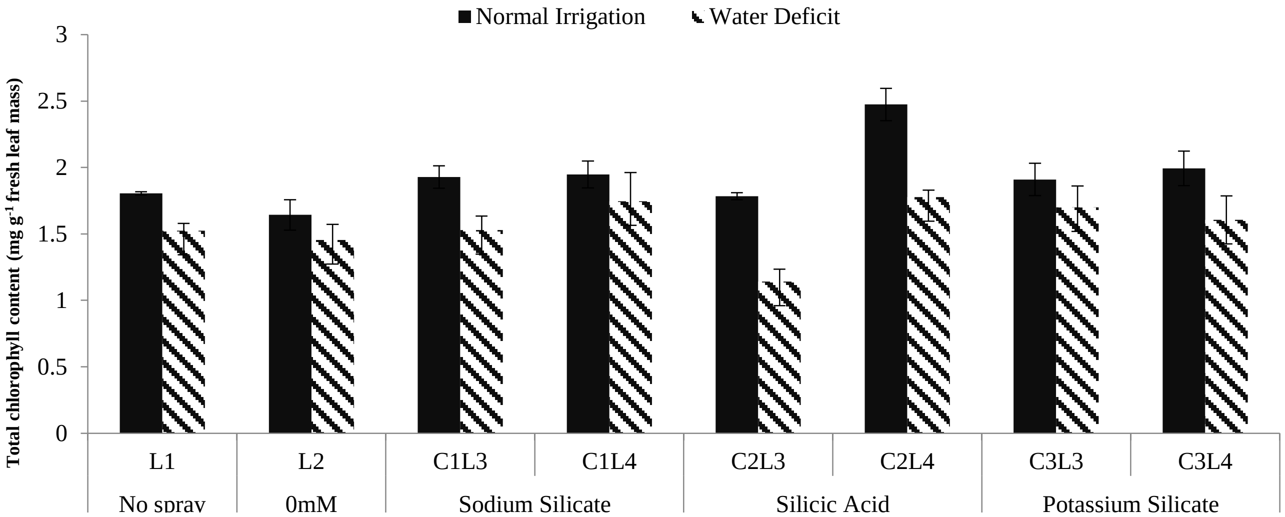

Fig. 5. Influence of different concentrations of silicon on total chlorophyll content (mg g^{-1} fresh leaf mass) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

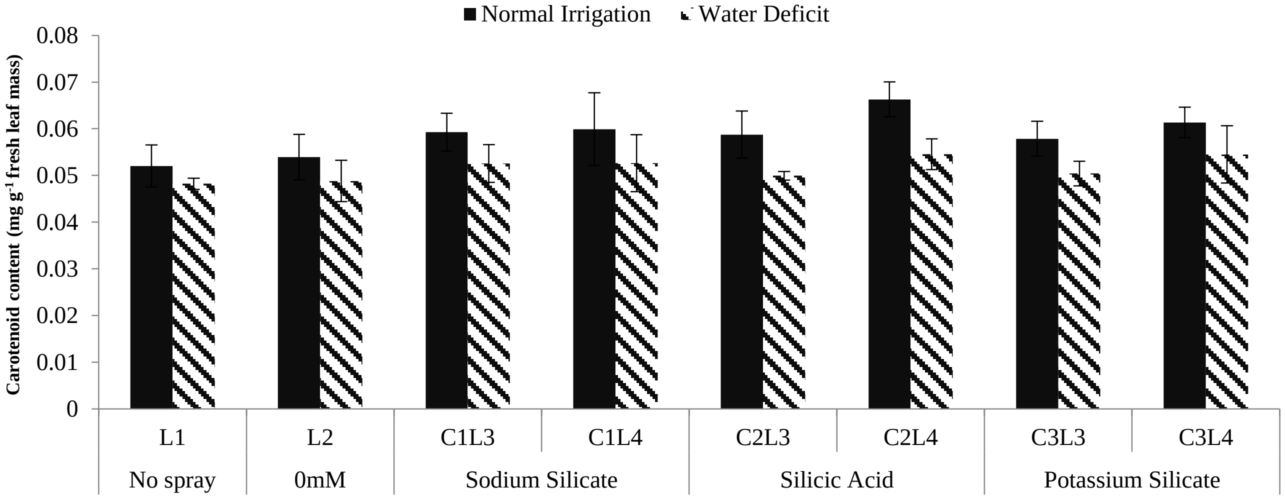

Fig. 6. Influence of different concentrations of silicon on carotenoids content (mg g^{-1} fresh leaf mass) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

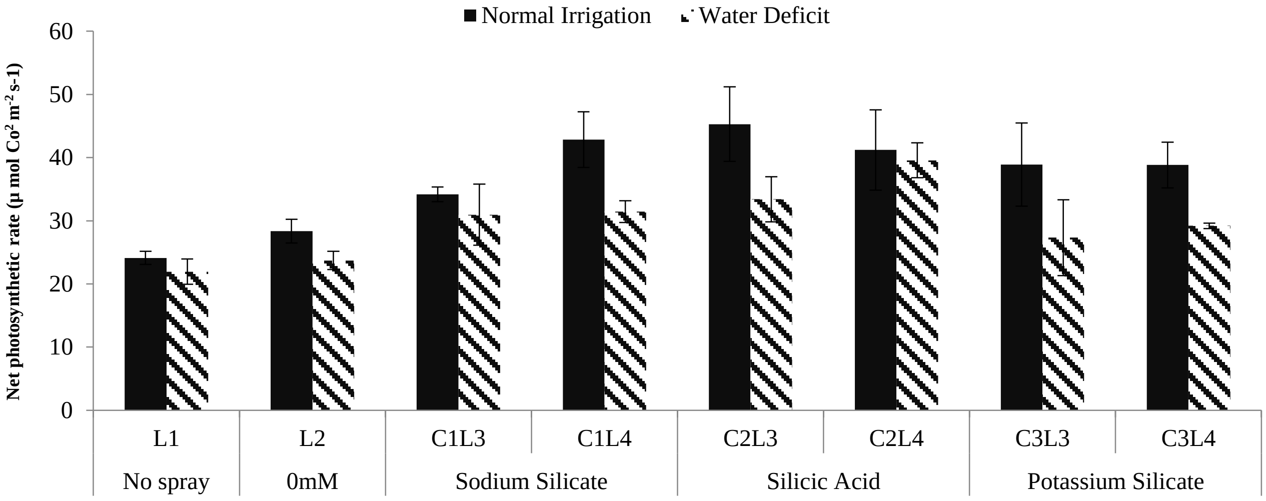

Fig. 7. Influence of different concentrations of silicon on net photosynthetic rate (µ mol Co_2 m^{-2} s^{-1}) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

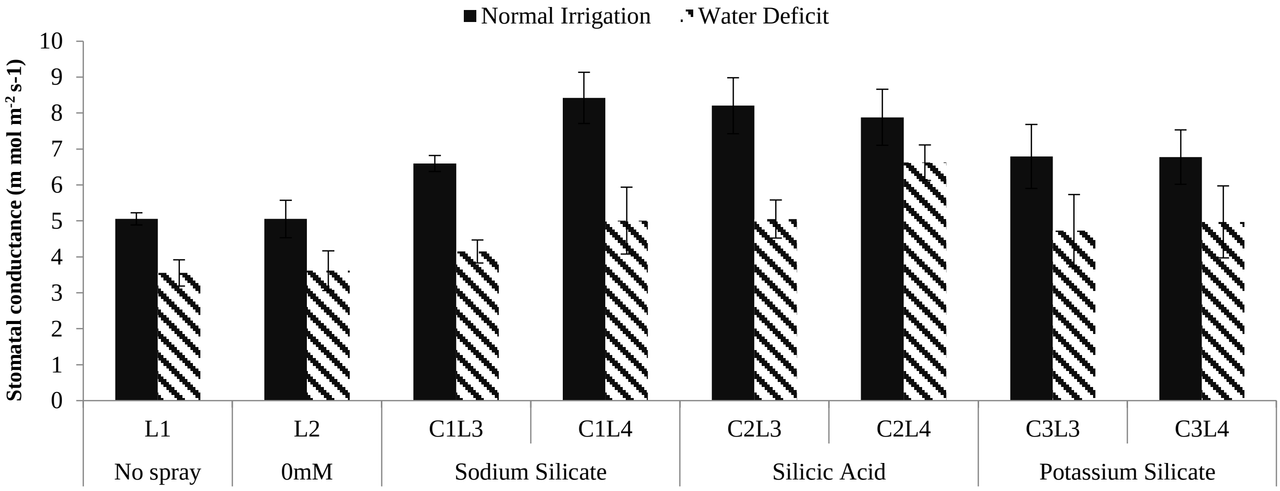

Fig. 8. Influence of different concentrations of silicon on stomatal conductance (m mol m^{-2} s^{-1}) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

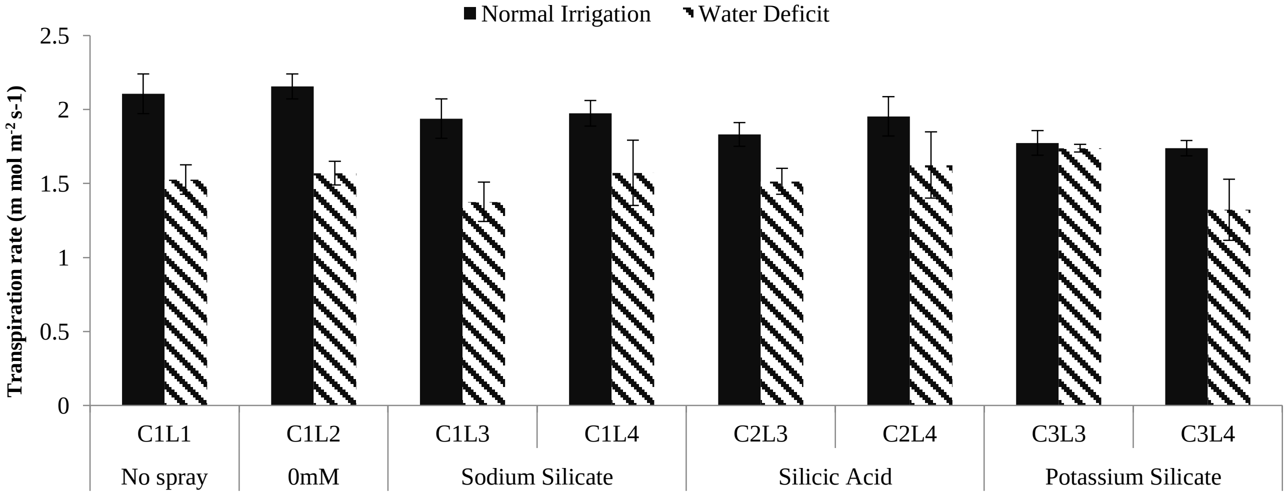

Fig. 9. Influence of different concentrations of silicon on transpiration rate (m mol m^{-2} s^{-1}) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

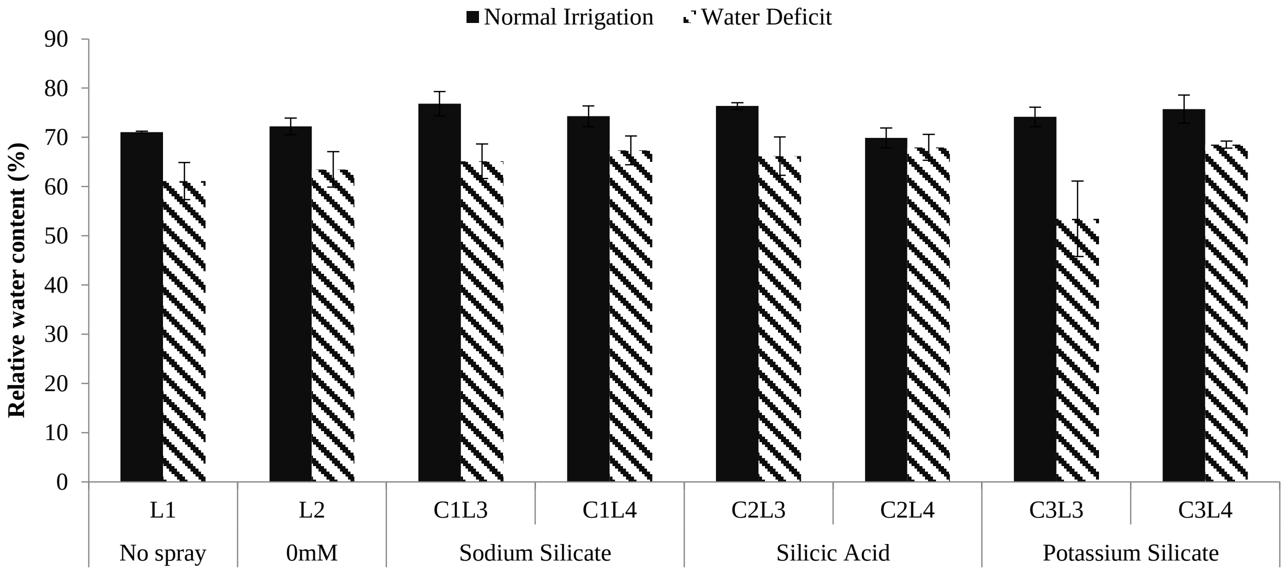

Fig. 10. Influence of different concentrations of silicon on relative water content (%) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

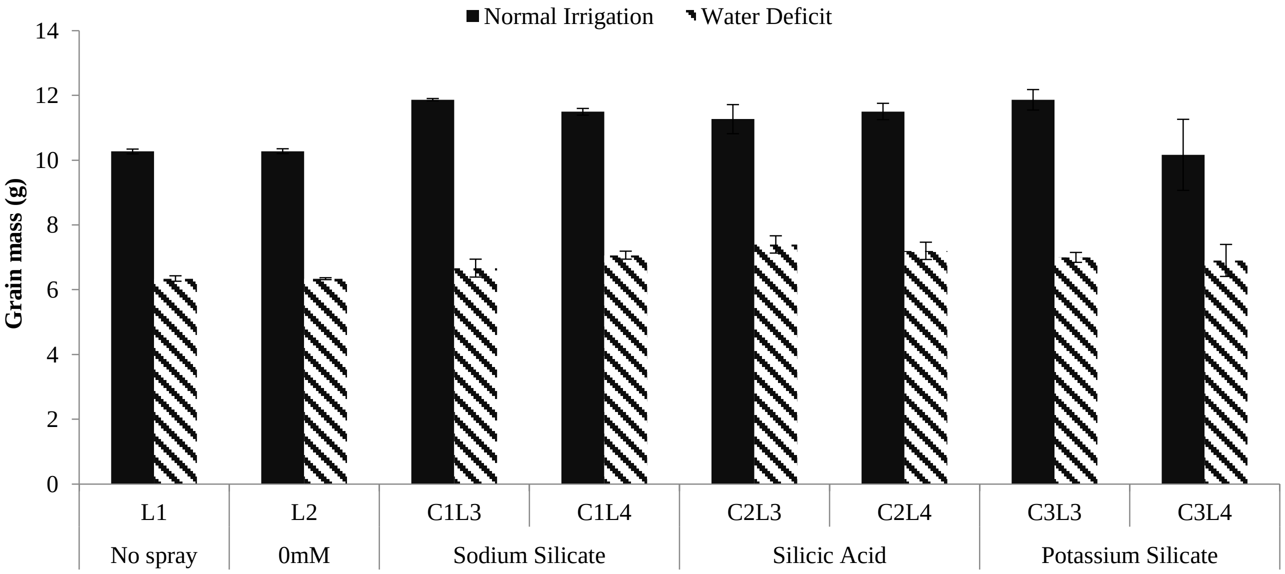

Fig. 11. Influence of different concentrations of silicon on grain mass (g) of wheat plants grown under water deficit environment (key to figure: L1= no spray, L2= 0 *mM*, C1L3=0.01 *mM* sodium silicate, C1L4=0.1 *mM* sodium silicate, C2L3= 0.01 *mM* silicic acid, C2L4=0.1 *mM* silicic acid, C3L3=0.01 *mM* potassium silicate, C3L4=0.1 *mM* potassium silicate).

It has been demonstrated that water paucity can impair cell elongation and expansion, eventually lowering fresh and dry matter output in crop plants (Anjum *et al.*, 2003b; Kusaka *et al.*, 2005). The extremely significant (36%) drop in fresh weight of plants grown under reduced water supply compared to those cultivated regularly watered seen during the current study might be attributed to a decline in both of the aforementioned processes. Under the water stressed environment, production of greater plants biomass has been considered as a positive attributes of plants towards stress tolerance (Farooq *et al.*, 2009). During the current experiment, Si was used to obtain the same result. The considerably greater biomass value in 0.1mM silicic acid treated plants may be explained by the findings of Maghsoudi *et al.*, (2015). It shows how the use of Si promotes plant biomass output by reducing electrolyte leakage and improving membrane stability.

Maintaining the proper leaf area is supportive to increase the photosynthesis and thus dry matter under drought (Wullschleger *et al.*, 2005). The significant reduction in leaf area due to water stress as observed during present study had also been reported in some other plants like, populous, soybean and grass species (Zhang *et al.*, 2004; Wullschleger *et al.*, 2005; Farooq *et al.*, 2009). The increased values of leaf area in water stressed wheat plants by the foliar application of Si as recorded during current investigation had also been reported by Maghsoudi *et al.*, (2015) in wheat cultivars. The application of the Si containing fertilizer had been reported in rice, wheat and sugarcane to improve quality and yield attributes (Savant *et al*., 1999; Pereira *et al*., 2004). It had been reported that with the application of the Si increased the leaf area, plant height and dry mass of the wheat leaves under water stress (Guevel *et al*., 2007). Moreover, the application of silicon helped to increase the growth and leaf area of the plants by maintaining the turgor pressure and structural integrity under drought stress (Abro *et al*., 2009).

The photosynthetic pigments have a crucial role in terms of electron transport chain and light harvesting system and had been found to directly related with photosynthetic activities of plants (Farooq *et al*., 2009). The reduction in photosynthetic pigments (Chl a, b, total chlorophyll) under water stress as recorded during present investigation in wheat plants had also been reported in rice (Chen *et al*., 2011), sorghum (Lux *et al*., 2003) as well as in wheat (Gong *et al*., 2003, Edward & Wright, 2008). The reduction in photosynthetic pigment under water deficiency could be explained by the production of the reactive oxygen species (ROS) that affect the photochemical efficiency of the plants and hence the chlorophyll pigment (Al-aghabary, 2005).The improvements in the chlorophyll contents by application of the silicon as revealed by the results of current study may be related with the higher levels of antioxidants in wheat (unpublished data), as the addition of the Si enhanced the tolerance of tomato plants towards ROS that ultimately helped to improve the pigmentation of plants (Al-aghabary, 2005).

The reduction in most important phenomenon of the plants; photosynthesis and related attributes, transpiration, stomatal conductance and relative water content due to limited water supply as recorded during present investigation had been well reported by some other studies (Yordanov *et al*., 2000; Nawaz *et al*., 2010; Chen *et al*., 2011). This reduction in the photosynthesis might be due to decrease in the relative water contents and leaf water potential (Lawlor & Cornic, 2002) or due to stomatal closure, feedback inhibition and degradation of photosynthetic pigments (Vasantha *et al*., 2010). The increase in photosynthetic efficiency of water stressed plants under silicon application as observed during current investigation might be due to enhancements in photosynthetic pigments and stomatal conductance in the treated plants (Vasantha *et al*., 2010). The results of Maghsoudi *et al*., (2015) had also revealed that foliar application of Si increased the leaf relative water contents and photosynthetic pigments (chlorophyll a, b and total chlorophyll as well as carotenoids) of wheat cultivars. Moreover, the silicon absorbed by plants in the form of silicic acid ultimately deposited as silica that helped to reduce the transpiration and improved photosynthesis of the plants (Canny, 1990; Sangster *et al*., 2001). The foliar feeding of the silicon compounds had also been observed to reduce the transpiration rate of the plants by the deposition of the silica that helped to improve its water related parameters in plants grown under less water availability (Gao *et al*., 2004).

Conclusion

Considering the results of current investigation, it can be concluded that silicic acid is the most suitable source of silicon compared for foliar application to mitigate the negative effects of water shortage in wheat. The wheat yield in the arid zone may be improved with foliar applications of silicic acid and in future it may be considered as facilitator molecule to understand the drought tolerance mechanism at molecular level in cereals especially wheat.

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References

Abro, S.A., R. Qureshi, F.M. Soomro, A.A. Mirbahar and G.S. Jakhar. 2009. Effects of silicon on growth and yield of wheat in silty loam soil. *Pak. J. Bot*., 41: 1385-1390.

Al-aghabary, K., Z. Zhu and Q. Shi. 2005. Influence of silicon supply on chlorophyll content, chlorophyll fluorescence, and antioxidative enzyme activities in tomato plants under salt stress. *J. Plant Nutr*., 27: 2101-2115.

Andrew, J.S., H. Moreau, M. Kuntz, G. Pagny, C. Lin, S. Tanksley and J. McCarthy. 2008. An investigation of carotenoid biosynthesis in Coffea canephoraand Coffea arabica. *J. Plant Physiol*., 165: 1087-1106.

Anjum, F., M. Yaseen, E. Rasul, A. Wahid and S. Anjum. 2003a. Water stress in barley *(Hordeum vulgare* L.). II. Effect on chemical composition and chlorophyll contents. *Pak. J. Agri. Sci.*, 40: 45-49.

Anjum, F., M. Yaseen, E. Rasul, A. Wahid and S. Anjum. 2003b. Water stress in barley (*Hordeum vulgare* L.). I. Effect on morphological characters. *Pak. J. Agri. Sci*., 40: 43-44.

Bakhat, H.F., Z. Zia, S. Fahad, S. Abbas, H.M. Hammad, A.N. Shahzad and M. Shahid. 2017. Arsenic uptake, accumulation and toxicity in rice plants: Possible remedies for its detoxification: A review. *Environ. Sci. Pollut. Res*., 24: 9142-9158.

Barrs, H.D. and P.E. Weatherley. 1962. A re-examination of the relative turgidity technique for estimating water deficits in leaves. *Aust. J. Biol. Sci*., 15: 413-428.

Buck, G.B., G.H. Korndorfer, A. Nolla and L. Coelho. 2008. Potassium silicate as foliar spray and rice blast control. *J. Plant Nutr*., 31: 231-237.

Canny, M.J. 1990. What becomes of the transpiration stream? *New Phytol*., 114: 341-368.

Carleton, A.E. and W.H. Foote. 1965. A comparison of methods for estimating total leaf area of barley plants. *Crop Sci*., 5: 602-603.

Chen, W., X. Yao, K. Cai and J. Chen. 2011. Silicon alleviates drought stress of rice plants by improving plant water status, photosynthesis and mineral nutrient absorption. *Biol. Trac. Elem. Res*., 142: 67-76.

Davies, B. 1976. Carotenoids. P. 38-165. In Chemistry and biochemistry of plant pigments. (Ed.): T.W. Goodwin. (2nd Ed.) Academic Press, London.

Denby, K. and C. Gehring. 2005. Engineering drought and salinity tolerance in plants: lessons from genome-wide expression The Scientific World Journal profiling in Arabidopsis. *Trends in Biotechnol*., 23: 547-552.

Edward, D. and D. Wright. 2008. The effects of winter waterlogging and summer drought on the growth and yield of winter wheat *(*Triticum *aestivum* L.). *Europ. J. Agron*., 28: 234-244.

Epstein, E. 1999. Silicon. Ann. Rev. Plant Physiol. *Plant Mol. Biol*., 50: 641-664.

Epstein, E. and A.J. Bloom. 2003. Mineral Nutrition of Plants: Principles and Perspectives, 2nd Ed., John Wiley and Sons, New York.

Epstein, E. and A.J. Bloom. 2005. *Mineral Nut Plants: Principles and Perspectives,* 2nd Edn. Sunderland: Sinauer Associates Inc.

Farooq, M., A. Wahid, N. Kobayashi, D. Fujita and S.M.A. Basra. 2009. Plant drought stress: effects, mechanisms and management. *Agron. Sust. Develop*., 29: 185-212.

Fawe, A., J.G. Menzies, M. Chérif and R.R. Bélanger. 2001. Silicon and disease resistance in dicotyledons. In: *Stud. Plant Sci*., 8: 159-169, Elsevier.

Gao, X., P. Zou, C.Q. Wang and F.S. Zhang. 2004. Silicon improves water use efficiency in maize plants. *J. Plant Nutr*., 27: 1457-1470.

Gong, H., K. Chen, G. Chen, S. Wang and C. Zhang. 2003. Effects of silicon on growth of wheat under drought. *J. Plant Nutr*., 26: 1055-1063.

Guevel, M.H, J.D.R. Menzies and R. Belanger. 2007. Effect of root and foliar applications of soluble silicon on powdery mildew control and growth of wheat plants. *Europ J. Plant Pathol*., 119: 429-436.

Iqbal, N., M.Y. Ashraf and M. Ashraf. 2011. Modulation of endogenous levels of some key organic metabolites by exogenous application of glycine betaine in drought stressed plants of sunflower (*Helianthus annuus* L.). *Plant Grow. Reg*., 63: 7-12.

Jaleel, C.A, P. Manivanna, A. Wahid, M. Farooq, R. Somasundaram and R. Panneerselvam, 2009. Drought stress in plants: a review on morphological characteristics and pigments composition. *Int. J. Agri. Biol*., 11: 100-105.

Jaleel, C.A., P. Manivannan, A. Kishorekumar, B. Sankar, R. Gopi, R. Somasundaram and R. Panneerselvam. 2007. Alterations in osmoregulation, antioxidant enzymes and indole alkaloid levels in *Catharanthus roseus* exposed to water deficit. *Colloids and Surfaces B: Biointerfaces*, 59: 150-157.

Jaleel, C.A., R. Gopi, B. Sankar, M. Gomathinayagam and R. Panneerselvam. 2008. Differential responses in water use efficiency in two varieties of Catharanthus roseus under drought stress. *Comp. Rend. Biol*., 33: 42-47.

Khadka, K., H.J. Earl, M.N. Raizada and A. Navabi. 2020. A physio-morphological trait-based approach for breeding drought tolerant wheat. *Front. Plant Sci.*, 11-715.

Kim, S.G., K.W. Kim, E.W. Park and D. Choi. 2002. Silicon-induced cell wall fortification of rice eaves: A possible cellular mechanism of enhanced host resistance to blast. *Phytopathol*., 92: 1095-1103.

Kim, Y.H., A.L. Khan, M. Waqas and I.J. Lee. 2017. Silicon regulates antioxidant activities of crop plants under abiotic induced oxidative stress: A Review. *Front. Plant Sci*., 8: 5-10.

Kusaka, M., M. Ohta and T. Fujimura. 2005. Contribution of inorganic components to osmotic adjustment and leaf folding for drought tolerance in pearl millet. *Physiol. Plant*., 125: 474-489.

Lawlor, D.W. and G. Cornic. 2002. Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. *Plant Cell Environ*., 25: 275-294.

Liang, Y., W. Sun, Y.G. Zhu and P. Christie. 2007. Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: a review. *Environ. Pollut*., 147: 422-428.

Lobell, D. and S. Gourdji. 2012. The influence of climate change on global crop productivity. *Plant Physiol*., 112.

Lux, A., M. Luxová, J. Abe, E. Tanimoto, T. Hattori and S. Inanaga. 2003. The dynamics of silicon deposition in the sorghum root endodermis. *New Phytol*., 158: 437-441.

Ma, J.F. 2004. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. *Soil Sci. Plant Nutr*., 50: 11-18.

Ma, J.F. and E. Takahashi. 2002. Soil, fertilizer, and plant silicon research in Japan. Elsevier.

Maghsoudi, K., Y. Emam and M. Ashraf. 2015. Influence of foliar application of silicon on chlorophyll fluorescence, photosynthetic pigments, and growth in water-stressed wheat cultivars differing in drought tolerance. *Turk. J. Bot*., 39: 625-634.

Massacci, A., S.M. Nabiev, L. Pietrosanti, S.K. Nematov, T.N. Chernikova, K. Thor and J. Leipner. 2008. Response of the photosynthetic apparatus of cotton (*Gossypium hirsutum*) to the onset of drought stress under field conditions studied by gas-exchange analysis and chlorophyll fluorescence imaging. *Plant Physiol. Biochem*., 46: 189-195.

Nakayama, N., H. Saneoka, R.E. Moghaieb, G.S. and K. Fujita. 2007. Response of growth, photosynthetic gas exchange, translocation of 13 C-labelled photosynthate and N accumulation in two soybean (*Glycine max* L. Merrill) cultivars to drought stress. *Int. J. Agri. Biol*., 9: 669-674.

Nawaz, K., K. Hussain, A. Majeed, F. Khan, S. Afghan and K. Ali. 2010. Fatality of salt stress to plants: Morphological, physiological and biochemical aspects. *Afr. J. Biotechnol*., 9: 5475-5480.

Nezhadahmadi, A., Z.H. Prodhan and G. Faruq. 2013. Drought tolerance in wheat. *The Sci. World J*., 13: 1-13.

Noori, S.S. and T. McNeilly. 2000. Assessment of variability in salt tolerance based on seedling growth in *Triticum durum*. *Gen. Res. Evol*., 47: 285-291.

Pereira, H.S., G.H. Korndorfer, A.D. Vidal and M.S. de Camargo. 2004. Silicon sources for rice crop. *Scientia. Agri. Cola*., 61: 522-528.

Rodrigues, F.A., F.X.R. Vale, L.E. Datnoff, A.S. Prabhu and G.H. Korndorfer. 2003. Effect of rice growth stages and silicon on sheath blight development. *Phyto. Pathol*., 93: 256-261.

Sahebi, M., M.M. Hanafi, S.N.A. Abdullah, M.Y. Rafii, P. Azizi, N. Nejat and A.S. Idris. 2014. Isolation and expression analysis of novel silicon absorption gene from roots of mangrove (*Rhizophora apiculata*) via suppression subtractive hybridization. *Bio.Med. Res. Inter.,* https://doi.org/10.1155/2014/971985

Saleem, M., S. Ali, M. Rehman, M. Rana, M. Rizwan, M. Kamran, M. Imran, M. Riaz, M. Hussein, A. Elkelish and L. Lijun. 2020a. Influence of phosphorus on copper phytoextraction via modulating cellular organelles in two jute (*Corchorus capsularis* L.) varieties grown in a copper mining soil of hubei province, China. Chemosphere. DOI 10.1016/j.chemosphere.2020.126032.

Saleem, M.H., S. Ali, M.F. Seleiman, M. Rizwan, M. Rehman, N.A. Akram, L. Liu, M. Alotaibi, I. Al-Ashkar and M. Mubushar. 2019. Assessing the correlations between different traits in copper-sensitive and copperresistant varieties of jute (*Corchorus capsularis* L.). *Plants*, 8(12): 545.

Saleem, M.H., S. Fahad, S.U. Khan, M. Din, A. Ullah, A.E.L. Sabagh, A. Hossain, A. Llanes and L. Liu. 2020c. Copperinduced oxidative stress, initiation of antioxidants and phytoremediation potential of flax (*Linum usitatissimum* L.) seedlings grown under the mixing of two different soils of china. *Environ. Sci. & Pollut. Res*., 27(5): 5211-5221. Available from https://doi.org/10.1007/s11356-019-07264- 7. DOI 10.1007/s11356-019-07264-7.

Saleem, M.H., S. Fahad, S.U. Khan, S. Ahmar, M.H.U. Khan, M. Rehman, Z. Maqbool and L. Liu. 2020b. Morphophysiological traits, gaseous exchange attributes, and phytoremediation potential of jute (*Corchorus capsularis* L.) grown in different concentrations of copper-contaminated soil. *Ecotoxicol. & Environ. Safety*, 189: 109915.

Sangster, A.G., M.J. Hodson and H.J. Tubb. 2001. Silicon deposition in higher plants. In: Silicon in Agriculture, (Eds.): Datnoff, L.E., G.H. Snyder, G.H. Korndorfer. pp 85-114. Amsterdam: Elsevier.

Savant, N.K., G.H. Korndorfer, L.E. Datnoff and G.H. Snyder. 1999. Silicon nutrition and sugarcane production: A review. *J. Plant Nutr*., 22: 1853-1903.

Sawatraksa, N., P. Banterng, S. Jogloy, N. Vorasoot and G. Hoogenboom. 2018. Chlorophyll fluorescence and biomass of four cassava genotypes grown under rain-fed upper paddy field conditions in the tropics. *J. Agron. Crop Sci.,* 204: 554-565.

Tassi, E., J.J. Pouget, G. Petruzzelli and M. Barbafieri. 2008. The effects of exogenous plant growth regulators in the phytoextraction of heavy metals. *Chemosphere*, 71: 66-73.

Thilagam, V.K., S. Mohanty, M. Shahid, R. Tripathi, A.K. Nayak and A. Kumar. 2014. Role of silicon as beneficial nutrient for rice crop. *Popular Kheti,* 2(1): 105-107.

Vasantha, S., S. Venkataramana, P.N. Rao and G.R. Gomathi. 2010. Long term salinity effect on growth, photosynthesis and osmotic characteristics in sugarcane. *Sugar Technol*., 12: 5-8.

Waqas, M.A., I. Khan, M.J. Akhter, M.A. Noor and U. Ashraf. 2017. Exogenous application of plant growth regulators (PGRs) induces chilling tolerance in short-duration hybrid maize. *Environ. Sci. Pollut. Res*., 24: 11459-11471.

Waraich, E.A., R. Ahmad, M. Saifullah, Y. Ashraf and Ehsanullah. 2011. Role of mineral nutrition in alleviation of drought stress in plants. *Aust. J. Crop Sci*., 5: 764-777.

Wullschleger, S.D., T.M. Yin, S.P. DiFazio, T.J. Tschaplinski, L.E. Gunter and M.F. Davis. 2005. Phenotypic variation in growth and biomass distribution for two advanced-generation pedigrees of hybrid poplar. *Can. J. For. Res*., 35: 1779-1789. doi: 10.1139/x05-101.

Yordanov. I., V. Velikova and T. Tsonev. 2000. Plant responses to drought, acclimation, and stress tolerance. *Photosynth*., 38: 171-186.

Zahedi, S.M., F. Moharrami, S. Sarikhani and M. Padervand. 2020. Selenium and silica nanostructure-based recovery of strawberry plants subjected to drought stress. *Sci. Reports*, 10(1): 1-18.

Zhang, J., B. Poudel, K. Kenworthy, J.B. Unruh, D. Rowland, J.E. Erickson and J. Kruse. 2019. Drought responses of above-ground and below-ground characteristics in warm-season turfgrass. *J. Agron. Crop. Sci*., 205: 1-12.

Zhang, J.Z., R.A. Creelman and J.K. Zhu. 2004. From laboratory to field. Using information from Arabidopsis to engineer salt, cold, and drought tolerance in crops. *Plant Physiol.*, 135: 615-621.

Zia, Z., H.F. Bakhat, Z.A. Saqib, G.M. Shah, S. Fahad, M.R. Ashraf and M. Shahid. 2017. Effect of water management and silicon on germination, growth, phosphorus and arsenic uptake in rice. *Ecotoxicol. Environ. Safety*, 144: 11-18.

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