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Full Length Research Paper

Silicon application and drought tolerance mechanism of sorghum

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Pot experiments were conducted at the PMAS, Arid Agriculture University, Rawalpindi, Pakistan during 2007 repeated during 2008 to study the effect of silicon and nanoirrigation (W_{40}) on drought tolerance mechanism of sorghum. According to experimental design, the silicon fertilization was divided into two levels: control (no application of potassium silicate) Si_0 and application of silicon Si_{200} (200 mlL^{-1} of potassium silicate per kg of soil). Irrigation was divided into two levels: crop upper limit (40 mm) irrigation denoted as W_{40} and without irrigation, crop lower limit as Wo. Each treatment was replicated three times with two sorghum cultivars: PARC SS-2 (drought tolerant) and Johar-1(drought susceptible). The results showed that increase in silicon leads to increase in leaf area index (LAI), specific leaf weight (SLW), chlorophyll content (SPAD), leaf dry weight (LDW), shoot dry weight (SDW), root dry weight (RDW), total dry weight (TDW) and remarkably decrease in leaf water potential and shoot to root ratio in sorghum cultivars compared to control treatment. When silicon concentration is applied with irrigation LAI, SPAD, LDW, SDW, RDW, TDW, net assimilation rate (NAR), relative growth rate (RGR), leaf area ratio (LAR) and water use efficiency (WUE) increased by 30, 31, 40, 30, 28, 30, 27, 35, 32, 30 and 36% respectively as compared to water deficient treatment. These results suggest that silicon application may be useful to improve the drought tolerance of sorghum through the enhancement of water uptake ability.

Key words: Drought, leaf water potential, leaf area ratio, net assimilation rate, relative growth rate, nano-irrigation.

INTRODUCTION

Orthosilicic acid, Si $(OH)_4$ is main components of soil solution which provide silicon. It has pH < 9 with solubility of 1.7 mM at 25°C (Knight and Kinrade, 2001). Silicon is deposited in stems and leaves as hydrated silica ($SiO_2 \cdot nH_2O$) phytoliths by evapotranspiration path (Sangster et al., 2001). In the dry and semi dry regions, water is limiting factor for crop growth and regrettably, conventional technology of irrigation does not avoid elevated losses of plant-available water due to evapotranspiration and leaching. The watering with silicon allows a reduction in leaching, but does not affect evapotranspiration. Roots weight and volume increases by 20 to 200% due to optimum silicon fertilization which ultimately enhanced drought and salt resistance in cultivated plants. Soil fertility and texture have considerable correlation with Si compounds (Bocharnikova and Matichenkov, 2008).

Sorghum (*Sorghum bicolor* L) is the crop of arid regions in Asia and Africa because it can withstand and remain alive under environment of permanent or discontinuous drought by adjustment in leaf water potential (osmotic adjustment) and making dense root system. Reduction in sorghum yield as a result of variable precipitation or inadequate irrigation is the major problem (CGIAR, 2007). Sorghum is the fifth most significant cereal crop worldwide in both area and metric tons harvested (FAO, 2009). Sorghum is stress tolerance crop and its adjustment to secondary lands has been well recognized. Sorghum as an optional cereal crop for more adequate,

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Table 1. Physiochemical characteristic of the soil before and after the application of silicon.

Characteristic	Unit	Values(before sowing)	Values(after silicon application)
EC	dsm^{-1}	0.35	0.75
pH	-	7.5	7.45
Saturation %	%	33.5	34.75
CEC	C mol kg^{-1}	9.15	9.85
Organic matter	%	0.41	0.40
Silicon in soil (SiO_3^{2-})	mg kg^{-1}	20.850	33.06
Soluble cations			
Ca^{2+} Mg^{2+}	meq l^{-1}	2.70	2.60
Soluble anions			
CO_3^{2-}	meq l^{-1}	0.50	0.41
HCO_3^{1-}	meq l^{-1}	2.45	2.10
$Cl1^-$	meq l^{-1}	3.00	2.45
$SO4^{2-}$	meq l^{-1}	0.37	0.40
Textural Class		Loam	Loam
Sand	%	57.30	57.30
Silt	%	23.80	23.80
Clay	%	19.00	19.00
Total nitrogen	%	0.031	0.024
K^+	mg kg^{-1}	78	69
Available P	mg kg^{-1}	6.75	6.25
DTPA extractable Zn	mg kg^{-1}	0.23	0.22
Bulk density	Mg m^{-3}	1.57	1.46
Total porosity	%	50.4	53.2

food production and food security in areas where moisture limitation and heat stress is a trouble for maize. The adaptability of Sorghum under increasing temperature and decreasing precipitation may help to alleviate crop losses. Drought tolerance in crops may be enhanced by application of certain mineral elements like Phosphorus (Alkaraki et al., 1996), Potassium (Egilla et al., 2001) and Calcium (Lux et al., 2003). Silicon, important mineral elements have accumulated in crops of Gramineae and Cyperaceae, ensuring superior growth, while its application has been reported to relieve the decrease in dry matter accumulation or photosynthetic rate (Liang et al., 1996) and heavy metals toxicity (Gu et al., 1998). A large amount of silicon accumulates in endodermal tissue (Lux et al., 2002) due to speedy uptake (Lux et al., 2003) recommend the option that silicon plays significant role in water uptake and root growth under water stress. In terms of the effect of silicon on sorghum, information regarding drought tolerance and water uptake ability is lacking. The present study was conducted to document the effects of silicon application under water-limited conditions on the drought tolerance of sorghum and how drought tolerance of sorghum may be enhanced by silicon. To complete this idea, two cultivars differing in drought tolerance were assessed for silicon application.

MATERIALS AND METHODS

Pot experiments were conducted at the PMAS, Arid Agriculture University Rawalpindi Pakistan during 2007 and repeated during 2008. Plastic pots having an area of 0.05 m^2 were filled with 8 Kg of the soil. Two Sorghum cultivars viz. PARC SS-2 (drought tolerant) and Johar-1 (drought susceptible) were grown under four treatments viz. T1= control (Si_0), T2= 200 ml L^{-1} of potassium silicate per kg of soil (Si_{200}), T3= Irrigation (100 % Field capacity) crop upper limit (W_{40}), T4= Without Irrigation (W_0) crop lower limit. The experimental design was CRD with three replicates of each treatment in which silicon application was in main plot while irrigation was in subplot. The soil was well drained alluvial loam (fine-silty, mixed, hyperthermic, vertic, ochraqualfs, USDA). The soil physiochemical characteristics are presented in Table 1. The pots were covered with aluminium foil to prevent an increase in soil temperature caused by solar radiation. As the source of potassium, potassium silicate was used in the silicon-applied treatment (Si_{200}) and potassium chloride in the silicon-deficient treatment (Si_0). The soil pH in all pots was adjusted to 7.6 with calcium hydroxide. Five seeds of sorghum cultivars were sown per pot. Plastic sheets coated with aluminum film were placed on the soil surface to prevent evaporation from the pots. The leaf water potential of the leaves was measured by a pressure chamber (Model 1000, PMS Instrument Co., Corvallis, OR) during the daytime (10.00 to14.00 h) at 50 DAS. The leaf blade, stem and roots were separately sampled

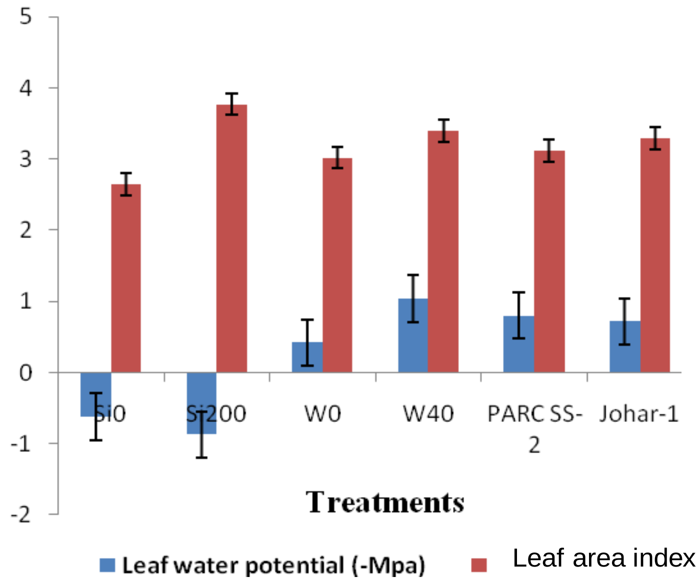

Figure 1. Effects of silicon application and irrigation treatment on the leaf water potential and Leaf area index of cv. PARC SS-2 and Johar-1.

at 30 DAS and 50 DAS for growth analysis. The leaf area was measured with a leaf area meter (CI-202 area meter CID, Inc) and the dry weight of each organ was recorded after drying samples in drying oven at 80°C for 72 h. Three plants from each treatment were used for statistical analysis. Growth analyses were performed on the basis of dry weight and leaf area measured. The relative growth rate (RGR), net assimilation rate (NAR) and leaf area ratio (LAR) was calculated according to the following formulae (Hunt, 1978):

$$RGR = \frac{\ln w2 - \ln w1}{t2 - t1}$$

$$NAR = \frac{w2 - w1}{t2 - t1} \times \frac{\ln L2 - \ln L1}{L2 - L1}$$

$$LAR = \frac{\ln w2 - \ln w1}{w2 - w1} \times \frac{L2 - L1}{\ln L2 - \ln L1}$$

Where w1 and w2 was the dry weight (g) at 30 DAS and 50 DAS while L1 and L2 were leaf area (m^2) on 30 DAS and 50 DAS, respectively.

The day's t1 and t2 are the initial and last days of the dry treatment period, respectively. Diurnal changes in the water content of the soil (average value of a whole pot) and the transpiration rate per unit leaf area were calculated from the transition of the pot weight and leaf area at 50 DAS. WUE was also calculated according to the following formula:

$$WUE = \frac{w2 - w1}{T}$$

Where T is the total amount of water used for transpiration during the dry treatment period.

The silicon concentration of the third-last fully expanded leaves was measured according to Lux et al. (2002). The dried powdered plant sample was ashed in a muffle oven at 500°C for 5 h. The plant ash was dissolved in diluted HCL (1: 1; 10 ml) at 100°C. The process of dissolving in HCL and evaporation to dryness was repeated three times. Then, diluted HCL (1: 1: 15 ml) was added and the sample was heated at 100°C, filtered, placed into a ceramic crucible and ashed again in the oven at 540°C for 5 h. After cooling, the weight of Si was determined gravimetrically. Data of both year experiments was pooled and analysed statistically by analysis of variance (ANOVA), with subsequent comparison of means by the least significant difference (LSD) test.

RESULTS

Effect on leaf water potential, leaf area index (LAI) and specific leaf weight (SLW)

The water potential of sorghum leaves were decreased under crop lower limit (Figure 1, Tables 2 and 4) while silicon applied plants still maintain higher water potential as compared to those without silicon fertilization and under no irrigation, which indicated that application of silicon improved the water status of stressed plants. The silicon applied in the form of potassium silicate has shown positive effect on leaf water potential as compared to control treatment. Irrigation at crop upper limit increases leaf water potential and interactive effect of both silicon and irrigation significantly contributed toward leaf water potential. Difference of leaf water potential (φ leaf) among cultivars indicated that both are different toward stress and PARC SS-2 responded good under stress, therefore this genotype can be considered as drought tolerant. The interactive effects revealed that leaf water potential were not significantly different among Si_{200} and Si_0 treatment. The lowest value for leaf water potential was recorded under Si_0W_0. The results were in

Table 2. Silicon and Irrigations two way interactive effects on leaf water potential, leaf area, leaf area index, specific leaf weight, SPAD, leaf dry weight, root dry weight and total dry weight of sorghum genotypes.

Treatments	Leaf water potential (-Mpa)	Leaf area index	SLW	SPAD	Leaf dry weight (g)	Shoot dry weight (g)	Root dry weight (g)	Total dry weight (g)
Interaction(Si x irrigation)	**	*	ns	*	*	**	*	*
$Si_{200}W_{40}$	0.38d	3.84a	199	86.05a	15.27a	35.10a	27.03a	62.14a
$Si_{200}W_0$	0.86b	3.71a	188.67	76.21a	9.50b	29.16b	23.65b	52.81b
Si_0 W_{40}	0.51c	2.95b	189.17	56.83b	7.69b	23.66c	14.54c	38.20c
Si_0W_{40}	1.22a	2.33c	177.83	56.58b	5.78c	19.55d	15.90c	35.46c
R^2	0.55	0.94	0.88	0.900	0.90	0.993	0.82	0.94
Interaction(Si x cultivar)	*	*	**	*	ns	*	*	*
Si_{200}PARC SS-2	0.67c	3.58b	190.33b	80.83a	13.33	37.05a	28.42a	65.47a
Si_{200}Johar-1	0.57bc	3.97a	202.33a	81.43a	11.44	27.21b	22.26b	49.47b
Si_0PARC SS-2	0.99a	2.66c	147.22d	57.00b	6.74	22.56c	15.99c	38.55c
Si_0Johar-1	0.86b	2.62c	167.17c	56.41b	6.74	20.65c	14.44c	35.10c
R^2	0.47	0.64	0.43	0.799	0.88	0.90	0.94	0.92
Interaction(Irrigation x Cultivar)	ns	ns	ns	ns	*	*	*	*
PARC SS-2W_0	1.08	3.33	185.17	73	12.61a	32.81a	23.03a	55.85a
Johar-1W_0	0.46	2.91	203	64.83	7.47c	26.79b	21.38ab	48.17b
PARC SS-2W_{40}	1.01	3.46	180	69.88	10.36b	25.94b	18.53bc	44.48bc
Johar-1W_{40}	0.42	3.13	186.5	67.96	7.82c	21.92c	18.16c	40.09c
R^2	0.27	0.0007	0.06	0.14	0.37	0.92	0.93	0.97

Data are the means of three replications. Different letters indicate significant differences by LSD (P, 0.05). NS, significant at the 0.1% and 5% level and not significant by analysis of variance (ANOVA), respectively. W_{40} = nanoirrigation, W_0 = crop lower limit, Si_{200} = silicon applied, Si_0 = silicon not applied.

Table 3. Silicon fertilizations and irrigations interactive effect on Shoot to root ratio, Silicon in leaf, Silicon in root, Silicon in soil, Transpiration rate, Net assimilation rate, Relative growth rate, Leaf area ratio and Water use efficiency of Sorghum genotypes.

Treatments	Shoot to root ratio	Silicon in leaf (mg)	Silicon in root(mg)	Silicon in soil (mg Kg^{-1})	Transpiration rate leaf area-1 (mmole H_2O cm^{-2} s^{-1})	Net assimilation rate (NAR) g m^{-2} day^{-1}g m^{-2} day^{-1}	Relative growth rate (RGR) g g^{-1} day^{-1}	Leaf area ratio(LAR) (x 10^{-4} m^2 g^{-1})	Water use efficiency (g kg^{-1})
Interaction (Si x Irrigation)	*	*	*	*	ns	*	*	*	*
$Si_{200}W_{40}$	1.29b	1.88a	5.94a	28.43a	3.25	47.25a	0.20a	73.81a	6.92a
$Si_{200}W_0$	1.23b	1.23b	5.38a	26.08b	3.82	39.11b	0.16b	63.87b	3.51c
Si_0 W_{40}	1.64a	0.0033c	2.44b	8.33c	6.27	25.37c	0.13c	53.59c	5.27b
Si_0W_{40}	1.29b	0.0075c	2.28b	9.09c	4.47	22.74c	0.13bc	51.74c	3.42c

Table 3 Contd.

R^2	0.08	0.89	0.87	0.827	0.36	0.94	0.80	0.93	0.46
Interaction (Si x Cultivar)	ns	*	*	*	*	*	*	*	*
Si_{200}PARC SS-2	1.30	1.26b	5.44a	28.41a	3.35b	53.44a	0.16b	71.54a	6.37a
Si_{200}Johar-1	1.22	1.86a	5.87a	26.11b	3.72b	32.92b	0.20a	66.14b	5.83a
Si_0PARC SS-2	1.46	0.0045c	2.44b	9.09c	5.25a	24.98c	0.14bc	53.25c	3.50b
Si_0Johar-1	1.46	0.0063c	2.29b	8.34c	5.49a	23.14c	0.13c	52.07c	3.43b
R^2	0.61	0.60	0.76	0.86	0.91	0.84	0.40	0.91	0.87
Interaction (Irrigation x Cultivar)	ns	*	ns	*	ns	*	ns	ns	ns
PARC SS-2W_0	1.47	0.75b	3.90	17.97a	4.67	42.87a	0.16	64.68	5.50
Johar-1W_0	1.29	0.51b	3.98	19.53a	3.93	35.55b	0.14	60.11	4.36
PARC SS-2W_{40}	1.46	1.13a	4.47	18.80a	4.84	29.75c	0.17	62.71	4.93
Johar-1W_{40}	1.23	0.73b	3.68	15.65b	4.36	26.31b	0.15	55.51	4.33
R^2	0.36	0.080	0.0044	0.34	3.00E-05	0.97	0.10	0.65	0.47

Data are the means of three replications. Different letters indicate significant differences by LSD (P, 0.05). NS, significant at the 0.1% and 5% level and not significant by analysis of variance (ANOVA), respectively. W40 = nanoirrigation, W_0 = crop lower limit, Si_{200} = silicon applied, Si_0 = silicon not applied.

supportive to early findings of (Ma JF, 2004) who reported that application of silicon increases the leaf water potential and improve the drought tolerance of sorghum.

LAI of sorghum cultivars at 50 DAS under two silicon treatments, two irrigation level and there interactive effects are listed in Tables 2 and 4. On the whole the value of LAI is high in silicon applied treatment as compared to silicon deficient treatment (Figure 1). The LAI in combination with silicon and irrigation was high as compared to silicon deficient drought treatment. Cultivar Johar yielded good response for leaf area toward silicon while interactive effects of cultivar, irrigation and silicon have shown significant difference. The results were not related with the earlier conclusion (Tsuji et al., 2001) who reported that plants in the silicon deficient drought treatment had a higher LAI, indicating a smaller leaf area per unit dry weight, it did not result in an increase in the total amount of dry matter production compared with the silicon applied irrigated treatment. In our study PARC SS-2 decreases its LAI confirming that cultivar can adapt itself by rolling its leaf according to changing environmental conditions like moisture stress.

Significant variation was observed on the application of silicon on specific leaf weight of sorghum and it was high in silicon applied treatment and this may be due to the accumulation of silicon in leaves, therefore increasing leaf weight (Figure 2). The supply of Si can increase resistance to fungal diseases by maintaining specific leaf weight (Samuels et al., 1994; Blaich and Grundhofer, 1998; Liang et al., 2005; Wiese et al., 2005), improve mechanical stability of stems and leaf blades (Idris et al., 1975; Adatia and Besford, 1986; Rafi et al., 1997). There is great variation in uptake of Si between plant species affecting on the specific leaf weight of crops. Takahashi et al. (1990) divided plants into four classes depending on leaf Si concentration. Excluders ("–") contain less than 0.5% Si (expressed in relation to the dry weight), and the three groups of accumulators contain Si over a range from "+" with 0.5 to 2% Si; "++" with 2 to 4% Si to "+++" with more than 4% Si. Rice (*Oryza sativa* L.), is an example of the last group ("+++"). Most grasses have Si concentrations between 1 to 2%, whereas most dicots are excluders. In the irrigated treatment specific leaf weight was increased as compared to non irrigated treatment and cultivar Johar-1 generated highest leaf weight as compared to PARC SS-2. The interactive effect between irrigation and silicon fertilization produced superior specific leaf weight as compared to non irrigated silicon deficient treatments with R^2 of 0.88 (Table 2). Significant interactive effect was seen between cultivar and silicon fertilization and larger specific

Table 4. Silicon application, irrigation and Sorghum genotypes interactive effect on Leaf water potential, Leaf area, Leaf area index, Specific leaf weight, SPAD, Leaf dry weight, Root dry weight and Total dry weight.

Treatments	Leaf water potential (-Mpa)	Leaf area index	SLW	SPAD	Leaf dry weight (g)	Shoot dry weight (g)	Root dry weight(g)	Total dry weight(g)	Shoot to Root ratio
Interaction(Si x Cultivar x Irrigation)	**	**	ns	*	*	ns	*	*	ns
$Si_{200}W_{40}$PARCSS-2	0.40d	3.73b	186.67	85.33a	17.42a	40.67	30.20a	70.88a	1.34
$Si_{200}W_{40}$Johar-1	0.36d	3.95a	211.33	86.77a	13.13b	29.51	23.87bc	53.40b	1.23
$Si_{200}W_{0}$PARCSS-2	0.94c	3.43c	184	76.33ab	9.23c	33.47	26.65ab	60.07b	1.25
$Si_{200}W_{0}$Johar-1	0.78c	3.98a	193.33	76.10ab	9.76c	24.84	20.65c	45.54c	1.20
$Si_{0}W_{40}$PARCSS-2	0.53d	2.94c	183.67	60.67bc	7.78cd	24.90	15.87d	40.83cd	1.59
$Si_{0}W_{40}$Johar-1	0.49d	2.96c	194.67	53.00c	7.60cd	22.30	13.20	35.67d	1.24
$Si_{0}W_{0}$PARC SS-2	1.21b	2.38d	176	53.33c	5.70d	20.19	16.11d	36.27d	1.32
$Si_{0}W_{0}$Johar-1	1.44a	2.28d	179.67	59.83bc	5.87d	18.98	15.68d	34.64d	1.67
CV	13.17	8.01	4.37	15.03	15.95	8.98	12.23	8.13	15.57
R^2	0.53	0.78	0.28	0.82	0.84	0.85	0.78	0.85	0.26

Data are the means of three replications. Different letters indicate significant differences by LSD (P, 0.05). NS, significant at the 0.1 and 5% level and not significant by analysis of variance (ANOVA), respectively. W40 = nanoirrigation, W_0 = crop lower limit, Si_{200} = silicon applied, Si_0 = silicon not applied.

leaf weight was produced by Johar-1 under silicon application. Three way interactive effects generated non significant variation about specific leaf weight (Table 4).

SPAD readings and silicon application

Chlorophyll content was measured in leaves by SPAD meter (Minolta, Tokyo, Japan) at 50 days after sowing and it was increased due to the application of silicon showing increase in photosynthetic activity as compared to silicon deficient treatments. The effect of irrigation was not significant on chlorophyll content (Figure 2). The contents of chlorophyll have some adjustment with K_2SiO_3 application in comparison with the control. It canbe concluded that there was an improvement in plant architecture, with increased contents of chlorophyll due to application of silicon as K_2SiO_3. The interactive effect between silicon fertilization and irrigation have shown significant variation with R^2 of 0.90 while cultivar response toward silicon application and irrigation is not significant (Table 2). SPAD readings have shown significant variations in the three way interactive effects with CV of 15.03 (Table 4).

Effect on above ground biomass

Leaf dry weight in four treatments showed significant difference at 50 day after sowing (Figure 3), indicating that the silicon application have increased the biomass by 65% as compared to control treatment. Meanwhile leaf dry weight in irrigated, silicon + irrigated accounted significant difference from non irrigated treatment which suggested that both irrigation and silicon fertilization positively correlated toward leaf biomass. The interactive effect of silicon, irrigation and cultivar for leaf dry weight have accounted significant difference and maximum result was obtained in silicon applied irrigated treatment by cultivar PARC SS-2 while minimum observed in case of silicon deficient, drought treatment by Johar-1 (Table 4).This may be reason that in the presence of silicon and irrigation plant can lead to rapid improvement of leaf biomass, just indicating the positive effect of elevated silicon on leaf biomass. The results were in supportive to early findings of Rodriguez et al. (1996) who reported that silicon and other elements improved dry matter production in both wet and dry conditions. The interaction between silicon treatments, irrigated and non irrigated treatments affected leaf dry weight.

Shoot dry weight at 50 DAS (Table 2) was significantly ($P < 0.05$) differed among cultivars and treatment. Mean value of the data indicated that maximum shoot dry weight was observed in PARC SS-2 (52.017 g) followed by Johar -1 42.289 g). Positive variations among the(cultivars have noted for silicon and irrigation. The data pertaining to response of sorghum cultivars under irrigated, non irrigated, Si applied

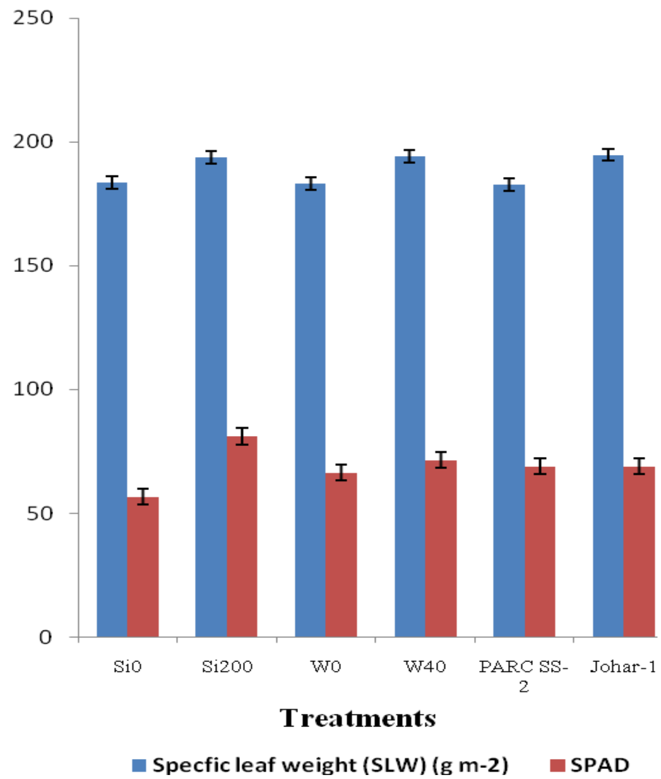

Figure 2. The values of specific leaf weight and SPAD index of sorghum under different treatments i.e. two silicon level, two irrigation and two cultivars.

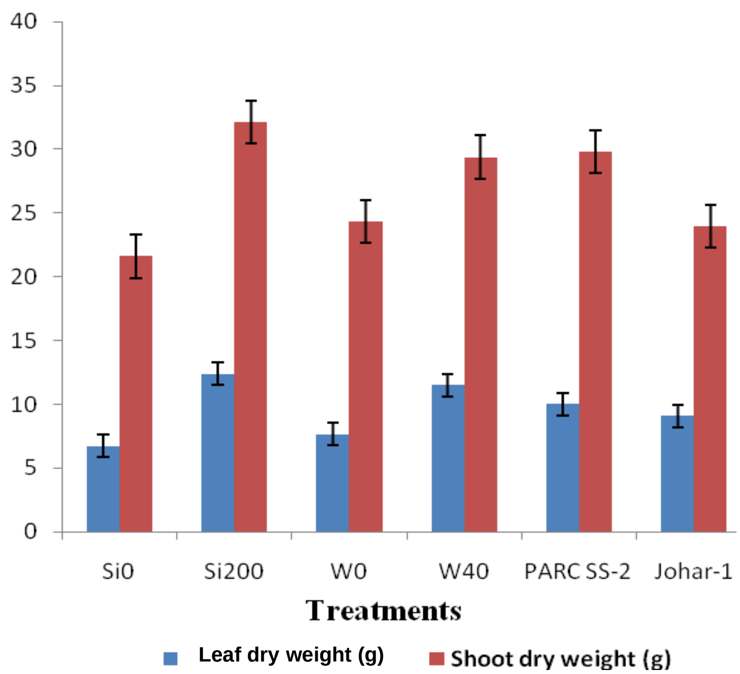

Figure 3. The values of leaf dry weight and shoot dry weight of sorghum under different treatments i.e. two silicon level, two irrigation and two cultivars.

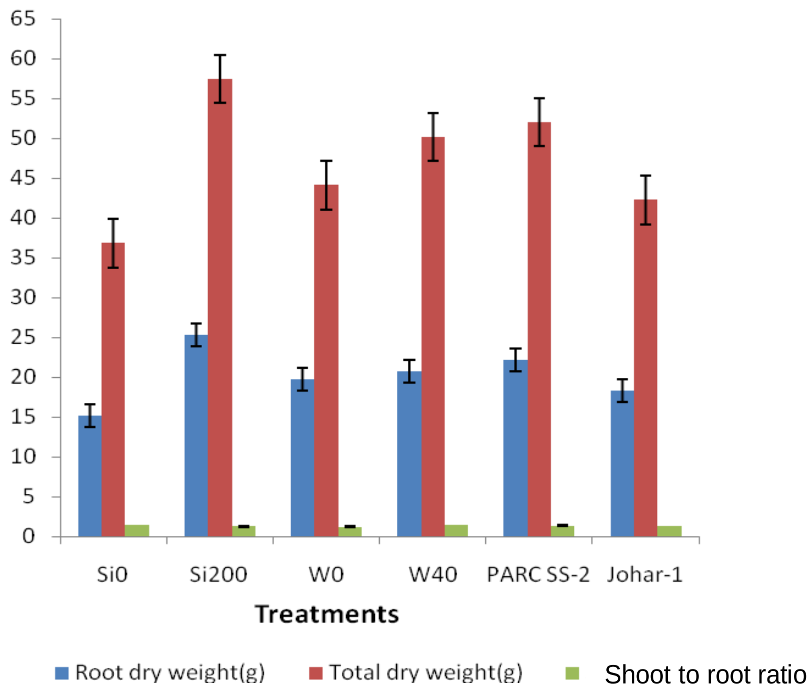

Figure 4. Effects of silicon application and irrigation treatment on the root dry weight, total dry weight and shoot to root ratio of two sorghum cv. PARC SS-2 and Johar-1 under different treatments.

(Si_{200}) and silicon deficient (Si_0) treatments accounted that shoot dry weight increases due to the application of silicon. Interactive effect related to treatments contributed well at 5% level of significance. The combined effect of silicon and cultivars depicted that silicon fertilization boosted shoot dry weight (Table 2). The maximum shoot dry weight was recorded in PARC SS-2 (37.05 g) under silicon applied (Si_{200}) while minimum was recorded in the Johar-1 (20.65 g) but under silicon deficient (Si_0) treatment. The collaborative effect of irrigation, crop lower limit and silicon level on cultivars reported that silicon shows good result under irrigated conditions in both cultivars confirming, silicon help in the uptake of water and its conversion to dry matter (Table 4). Thus present findings are in accordance with Tsuji et al. (2001; 2003) who concluded that dry weight of crops increases due to application of Silicon.

Effect on root dry weight, total dry weight and shoot/root ratio

Root development varied due to the application of silicon. Results discovered that silicon application influences the root dry weight under irrigated and dry treatment (Figure 4). At 50 DAS the root dry weight of the plants under silicon applied irrigated treatment was significantly higher than those given, the silicon deficient irrigated treatment (Table 2). The positive interactive effect of silicon application with cultivar was observed with R^2 of 0.8281. In the silicon deficient non irrigated treatment root dry weight decreased by 19% compared with silicon deficient irrigated treatment. The outcome of silicon on both cultivars showed a variant tendency toward root dry weight and it was higher in cultivar PARC SS-2 than in Johar-1(Figure 4). Combined effect of cultivars, silicon application and irrigation at 50 DAS accounted significant difference and maximum response was shown by PARC SS-2 under silicon applied irrigated treatment with R^2 of 0.78 (Table 4).

The silicon application increases the root dry weight by providing proper root moisture and root penetration. The results were at par with the findings of Tsuji et al. (2003) who reported that silicon fertilization increases the root efficiency by accumulating silicon in endodermis of root so high, root endodermal silification might be related to higher drought resistance in sorghum cultivars. The extra silicon applied in Si_{200} treatment generated significant increase in total dry weight (60% more in both years) at the 50 days after sowing of growing cycle (Figure 4). At 50 days after sowing, the total dry weight in the irrigated treatments is significantly higher than in non irrigated treatments. Total dry weight was 52% higher in PARC SS-2 than that in Johar-1 which indicated that irrigation and silicon fertilization as potassium silicate effects on total dry weight. Total dry weight of plants given the Si_{200} irrigated treatment was significantly higher than those given the Si_0 non irrigated treatment (Table 2). In the silicon deficient dry treatment, the plant dry weight decreased by 35 % compared with the silicon fertilized irrigated treatment. In contrast, the silicon fertilized dry treatment, the plant dry weight increased by 54% compared with silicon unfertilized non irrigated treatments. The results were in contradictory with the findings of (Tailchiro et al., 2003; Egilla et al., 2001, Li et al., 2003).

Shoot/root ratio at 50 days after sowing for two sorghum cultivars achieved significantly differences (Figure 4). The highest value was observed in PARC SS-2 (1.38) followed by Johar-1 (1.34). The shoot/root (S/R) in the silicon fertilized, irrigated treatments is significantly higher than in the silicon deficient and non irrigated treatments (Figure 3). S/Rs in the Si_{200}W40 and $Si_{200}W_0$ are 24 and 22% less than Si_0W_0 and Si_0W_0 which indicate that irrigation and silicon fertilizer application increases the root growth. S/Rs in the three way interactive effect of treatments have shown non significant difference with R^2 of 0.26 (Table 3). This result suggest that silicon application is mainly beneficial to the growth of root and its effect become more prominent in the presence of irrigation which stimulates the development of root system, allocating more matter to root system of plants. The results were in par with the findings of Tailchiro et al. (2003) who concluded that under dry conditions, silicon-applied sorghum had a lower shoot to root (S/R) ratio, indicating the facilitation of root growth and the maintenance of the photosynthetic rate and stomatal conductance at a higher level compared with plants grown without silicon application. The highest root to shoot ratio is obtained under silicon applied irrigated treatments in both cultivars which is close with the findings of Hattori et al. (2005), who suggested the possibility that silicon plays an important role in water transport and root growth of sorghum under drought conditions and this decreases the shoot root ratio.

Effect on silicon concentration in leaf and root

The results of silicon concentration in leaf are significant from each other (Figure 5). However, maximum silicon concentration was recorded in $Si_{200}W_{40}$ treatment followed by $Si_{200}W_0$ (Table 3).The results were in par to Takahashi and Miyake (1977) who distinguished between silicon accumulators and silicon non-accumulators and stated that sorghum (*Sorghum bicolor*) is one of the important silicon accumulators and most of the silicon in sorghum, as well as in other graminaceous species, is deposited in the outer walls of the epidermal cells of the leaves and in the inflorescence bracts (Hodson and Sangster, 1989). The epidermal cell walls are impregnated with a layer of silicon and become an effective barrier against both water losses by cuticular transpiration and fungal infections. In sorghum, and many other grasses, a high proportion of silicon in the leaf epidermis is also located intracellularly in specialized idioblasts called silica cells. Leaf epidermal silicification is well known in many grasses Lux et al. (2002). The results suggest that silicon fertilization and irrigation treatments help in maintaining pathogen resistance mechanism in plant leaves by providing strong silicification. Similarly plants can maintain good turgor potential under drought with the silicon fertilization. Silicon is deposited as a 2.5 mm layer in the space immediately beneath the thin (0.1 mm) cuticle layer, forming a cuticle–Si double layer in leaf blades. There are two types of silicified cells in leaf blades: silica cells, and silica bodies or silica motor cells. Silica cells are located on vascular bundles and are dumbbell-like in shape, whereas silica bodies are in bulliform cells of rice leaves. The silicification of cells proceeds from silica cells to silica bodies. In addition to leaf blades, silicified cells are also observed in the epidermis and vascular tissues of the stem, leaf sheath and hull. These depositions of Si protect plants from multiple abiotic and biotic stresses. The silicified cells also provide useful palaeoecological and archaeological information known as plant opal or phytoliths (Jian et al., 2001). Significant variation was also observed in the interactive effect of three treatments with R^2= 0.72 (Table 5).

Effect of silicon on root of sorghum cultivars under wet and dry conditions are presented in Figure 5. Statistically analysis of the data related to silicon in root pointed significant difference from each treatment. In case of interaction maximum silicon concentration in root was recorded in PARC SS-2 (4.08 mg) under irrigated treatment while minimum was recorded in Johar-1 under dry treatment. The interactive effect between cultivars and silicon fertilization shows that maximum silicon accumulation take place in PARC SS-2. The results were in close with the findings of earlier conclusions (Lux et al., 1999) who states that silicon accumulation in root increases its drought tolerance. These data, together with the high speed of silicon uptake and deposition by sorghum root (Lux et al., 2003), and the effects of losing root cell wall in sorghum (Hattori et al., 2005), suggest the possibility that silicon plays an important role in water transport and root growth of sorghum under drought conditions. Significant variation among three way interactive effects of treatments have observed with R^2 of 0.75 (Table 5).

Effect on transpiration rate, net assimilation rate (NAR), relative growth rate (RGR) and leaf area ratio (LAR)

Data pertaining to effect of silicon application and irrigation on the transpiration rate per unit leaf was non significant in case of cultivar (Figure 6). Transpiration rate decreased due to the application of silicon and it is due to the accumulation of silicon in leaves which act as a

Table 5. Silicon fertilization, irrigations and genotypes three way interactive effects on Shoot to root ratio, Silicon in leaf, Silicon in root, Silicon in soil, Transpiration rate, Net assimilation rate, Relative growth rate, Leaf area ratio and Water use efficiency.

Treatments	Silicon in leaf (mg)	Silicon in root(mg)	Silicon in soil (mg Kg^{-1})	Transpiration rate leaf area-1 (mmole H2O cm^{-2} s^{-1})	Net assimilation rate (NAR) g m^{-2} $day^{-1}g^{2}$ m day^{-1}	Relative growth rate (RGR) g g^{-1} day^{-1}	Leaf area ratio(LAR) (x 10^{-4} m^{2} g^{-1})	Water use efficiency (g kg^{-1})
Interaction (Si x Cultivar x Irrigation)	*	*	*	ns	*	*	*	*
$Si_{200}W_{40}$PARC SS-2	1.51b	5.12b	27.49a	3.24	59.73a	0.19ab	75.03a	7.53a
$Si_{200}W_{40}$Johar-1	2.26a	6.75a	29.38a	3.26	34.70c	0.21a	72.58a	6.31b
$Si_{200}W_{0}$PARC SS-2	1.01c	5.77ab	29.33a	3.47	47.11b	0.13c	68.04b	5.21c
$Si_{200}W_{0}$Johar-1	1.46b	4.99b	22.84b	4.18	31.10c	0.13ab	59.70c	5.34bc
$Si_{0}W_{40}$PARC SS-2	0.0026d	2.69c	8.452c	6.10	25.90d	0.12c	54.34b	3.48d
$Si_{0}W_{40}$Johar-1	0.0039d	2.20c	8.22c	6.43	24.78d	0.13c	52.84d	3.55d
$Si_{0}W_{0}$PARC SS-2	0.0064d	2.19c	9.73c	4.39	23.97d	0.15bc	52.17d	3.52d
$Si_{0}W_{0}$Johar-1	0.0087d	2.38c	8.46c	4.54	21.59d	0.12c	51.31d	3.32d
CV	14.86	16.93	7.33	16.75	8.24	13.88	3.49	13.15
R^2	0.73	0.76	0.79	0.36	0.73	0.44	0.91	0.86

Data are the means of three replications. Different letters indicate significant differences by LSD (P, 0.05). NS, significant at the 0.1 and 5% level and not significant by analysis of variance (ANOVA), respectively. W40 = nanoirrigation, W_0 = crop lower limit, Si_{200} = silicon applied, Si_0 = silicon not applied.

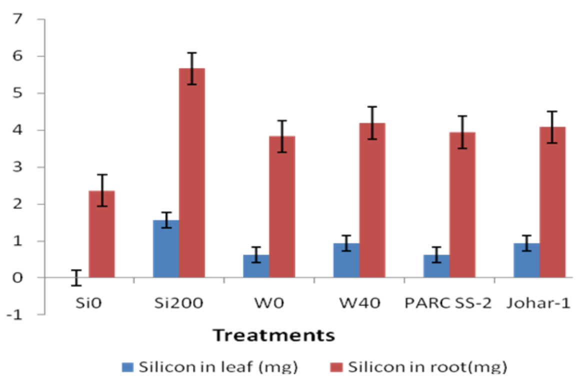

Figure 5. Silicon contents measured by Lux et al., (2002) in leaves and stems of Sorghum at third-last fully expanded leaves in 2007 and 2008 for two silicon level, two irrigation and two genotypes. Bars represent standard error.

barrier for water loss. Non significant interactive effect of silicon with irrigation is observed with R^2 of 0.36 (Tables 3 and 5). The transpiration rate of cultivar was measured at day time that is 1 pm where it was at its peak. Treatment effect shows that Si_{200} treatment can be used to lower transpiration rate and it can increase drought tolerance of cultivar. The results were in par with the findings (Hattori et al., 2005). In the experiment, NAR increased remarkably with the silicon fertilization and increase of water supply (Figure 6, Tables 3 and 5). The NAR in Si_{200}, W_{40}, PARC SS-2, $Si_{200}W_{40}$, Si_{200}PARC SS-2, PARC SS-2W_{40} and $Si_{200}W_{40}$ PARC SS2 are 43.2, 36.3, 39.1, 47.2, 53.4, 42.8 and 60% $gg^{-1}day^{-1}$, respectively, which 64, 54, 58, 35, 39, 32 and 22% greater than silicon deficient non irrigated Johar-1 treatments. Net assimilation rate for two cultivars of sorghum (Table 3) at 50 days after sowing pointed that decrease in net assimilation rate due to drought stress was significantly ameliorated by silicon application. However, maximum net assimilation was revealed in PARC SS-2 (42.87 g m^{-2} day^{-1}) followed by Johar-1 (35.55 g m^{-2} day^{-1}) under irrigated treatment. The minimum net assimilation rate was recorded in PARC SS-2 but under dry treatment. Similar results related to the effect of silicon on net assimilation rate and the effect of several other elements on drought tolerance and concluded that in terms of the improvement in growth under dry conditions, these elements seem to achieve this through the enhancement of dry matter production itself, rather than through the enhancement of properties responsible for drought tolerance (Egilla et al., 2001). The results are in par with the finding of (Rodriguez et al., 1996) who reported that silicon is distinct elements, as silicon-induced

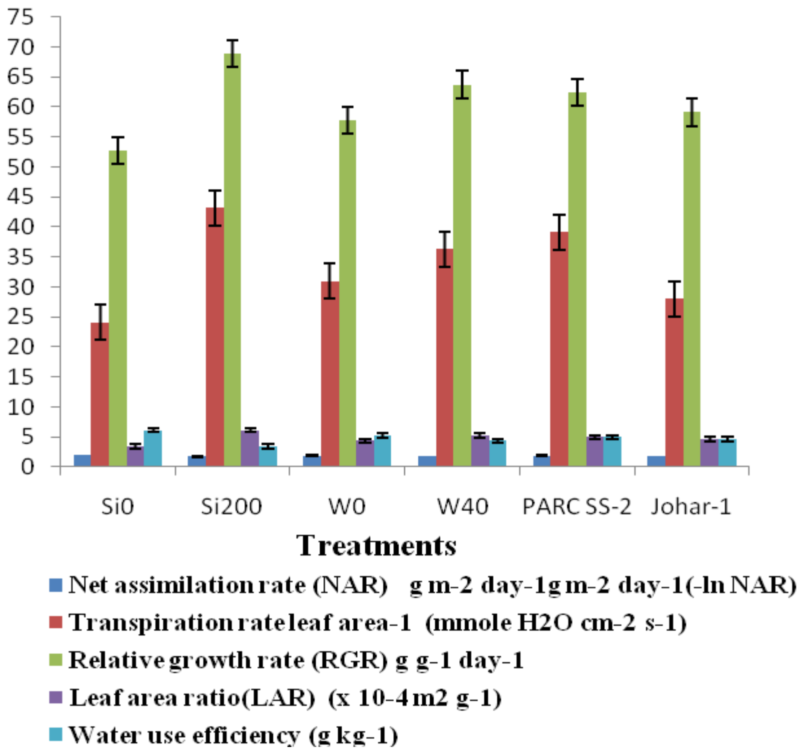

Figure 6. Effects of silicon application and irrigation treatment on the net assimilation rate, transpiration rate, relative growth rate, ratio and water use efficiency in the third last fully expanded leaf of cv. PARC SS-2 and Johar-1, data are the means of three replications.

accele-ration of dry matter production in sorghum is observed only when the plants are subjected to drought. Significant variation was observed due to the application of silicon on relative growth rate (Figure 6) but non significant difference was observed in irrigated treatments cultivars and interactions (Tables 3 and 5). The results were in contradictory to the earlier findings (Hattori et al., 2005).

Leaf area ratio was affected by the application of silicon (Figure 6). Results accounted that maximum leaf area ratio was due to application of silicon while minimum was shown by silicon deficient treatments. Irrigated treatments have also shown positive correlation toward LAR and it was 63.70 x 10^{-4} greater than dry treatment. PARC SS-2 generated highest LAR as compared to Johar-1. Silicon effect with irrigation and dry treatment are significantly different and greater LAR was recorded in silicon applied irrigated treatment with coefficient of determination (R^2) 0.93. Variant interaction were observed in cultivars with silicon and irrigation and cultivar PARC SS-2 responded good to silicon and irrigation with R^2 value of 0.92 and 0.66 respectively. Three way interactive effect among treatments have shown significant variation with R^2 of 0.91(Table 5). The results were in par with the earlier findings (Hattori et al., 2005) who reported that silicon application under dry treatment had a higher LAR, indicating a larger leaf area per unit dry weight.

Effect on water use efficiency (WUE)

WUE is calculated by the ratio of biomass produced by sorghum to actual total water use. The values of WUE in Si_{200}, W40, Si_{200}W40 are 6, 10, 5.22 and 6.92 g kg^{-1}, respectively which are significantly higher than silicon deficient dry treatments (Tables 3 and 5). This indicates that irrigation and silicon fertilization are favourable to the improvement of WUE (Figure 6). In addition interactive effect of silicon Si_{200}W40PARC SS-2 and $Si_{200}W_{40}$ Johar-1 are 7.05 and 6.31 higher than that in $Si_{200}W_0$PARC SS-2 and $Si_{200}W_0$Johar-1, those in Si_0W_{40}PARC SS-2 and Si_0W_{40} Joahr-1, 9 and 9.27% less than that in $Si_{200}W_{40}$PARC SS-2 and $Si_{200}W_{40}$ Johar-1, respectively, which suggest that elevated silicon is also favourable to the improvement of WUE. The increase in WUE suggests that silicon treatment is an optimal strategy for water management. The dry matter production of plants is determined by water consumption and WUE in addition to other factors. In the present study, although the WUE of sorghum increased with soil desiccation regardless of the cultivar, there were significant changes in WUE with silicon application under either dry or irrigated (Table 3). The results are in contradictory to the findings (Hattori et al., 2005) who reported that there is no significant effect of silicon on water use efficiency.

DISCUSSION

The outcome of the present experiment was that the silicon fertilization affected leaf water potential and leaf area index. Leaf water potential is main contributor toward good utilization of soil water content to photosynthate, provided that soil water content is not limiting, high levels of silicon tend to encourage maintenance of leaf water potential. Leaf water potential maintenance by adjusting RWC in leaves is known as an alternative measure of plant-water status, reflecting the metabolic activity in tissues (Flower and Ludlow, 1986). In the present study leaf water potential was dropped in silicon deficient dry treatment and this decrease in leaf water potential could be due to unavailability of water in the soil (Shalhevet, 1993) or root systems, which are not able to compensate for water lost by transpiration through a reduction of the absorbing surface (Gadallah, 2000).

The combined effects of silicon with irrigation are most remarkable, but without irrigation and no silicon fertilization the effect is inferior. In addition silicon deposited in the tissues helps to alleviate water stress by decreasing transpiration and improves light interception characteristics by keeping the leaf are index and specific leaf weight high (Epstein, 1999). Agarie et al. (1998) have shown that transpiration from leaves of rice plants is considerably reduced by the application of silicon. Our results obtained in this study support the above conclusion and reported the beneficial effect of silicon on the increase in LAI, shoot, root and total biomass, hence on the improvement of photosynthesis and good crop stand. LAI (at 50 days after sowing) in Si_{200} and W40 are 58 and 23% significantly higher than that in Si_0 and W_0. Correspondingly, Shoot/Root has been decreased (Figure 4 and Table 3), therefore, this beneficial effect of silicon on the sorghum growth may be due to good growth of root and hence changes in water use efficiency. Moreover these changes will be more distinct in the combination of silicon fertilization and irrigation. In terms of the improvement in growth under dry conditions, silicon and other elements seem to do enhancement of dry matter production itself, rather than through the enhancement of properties responsible for drought tolerance (Egilla et al., 2001; Li et al., 2003). All of these elements improved dry matter production in both wet and dry conditions (Rodriguez et al., 1996). The specificity of the effect of silicon to dry conditions indicates that silicon affects certain traits restricting dry matter production under water-limited conditions (Hattori et al., 2005). Silicon is an element that does not cause severe injury to plants when present in excess and can provide multiple benefits (Ma et al., 2006).

The positive effect of high silicon availability in leaf, increases source strength and it was well correlated with the drought tolerance and resistance to pathogen attacks (Figure 5). The results are in line with similar experiments in which source strength was manipulated by the application of silicon. Silicon containing products are thought that they can play an active role in plant protection against diseases (Jian et al., 2008). We propose that the overall effect of higher silicon availability in leaf, increases source strength and provide strength against diseases. The interactive effect of cultivar, silicon fertilization and irrigation has also shown positive correlation to source activity (Table 5). Silicon fertilization and irrigation treatment have shown good positive contribution toward NAR, RGR, LAR and negative correlation toward transpiration rate. This result suggests that increasing silicon contributes to provide crop stand under drought by converting single mole of water to photosynthate, but with irrigation it can give superior results. This results accord with conclusion that increasing silicon can stimulate NAR, RGR and LAR (Hattori et al., 2005) and decreases transpiration rate through the formation of a cuticle –silica double layer, maintaining a high leaf water potential (Yoshida, 1965;Matoh et al., 1991).

In most semi arid region of world, the lack of rainfall is the primary limiting factor for the crop development. There have been many reports on the increase in crop yield by irrigation and fertilization in semiarid regions (Blum et al., 1991; Blum and Johnson 1993; Clark et al., 1990; DeJuan et al., 1999; Li et al., 2001a; Hussain and Al-Jaloud, 1995; Katerji et al., 1998; Recio et al., 1999). In this experiment we have also explained the effects of irrigation and silicon fertilization on WUE. The main result are that irrigation and silicon fertilization stimulate the deeper and stronger root system, larger LAI and hence remarkably improved crop growth compared with nonirrigated and nonfertilized treatments. The highest WUE consistently occur with 40 mm irrigation and 200 mg kg^{-1} of silicon fertilization. It was also observed that the water use efficiency of +Si plants was significantly higher than that of –Si plants. The result observed were due to well-thickened layer of silica gel associated with the cellulose in the epidermal cell walls, which may help to reduce water loss, while an epidermal cell wall with less silica gel will allow water to escape at an accelerated rate. The interactive effects of treatments show that irrigation and silicon fertilization can improve the increase of LAI, R/S, NAR, RGR and LAR (Tables 2 and 5). Owing to the elevated trend of lack of rainfall in the background of global climatic changes (Qin, 2003) it is significantly practical to explore the irrigated effects of silicon fertilization in different combinations on the growth of different crops.

Conclusions

Drought tolerance of the crop is affected by the application of nutrients. The application of certain mineral elements to various crops can influence their drought tolerance or traits involved in drought tolerance. The modification of fertilizer composition is therefore considered to be a useful method to improve crop productivity under drought conditions. However, few effects on drought tolerance have been reported for elements other than the major nutrients. Certain seed plant species, mainly from the families Gramineae and Cyperaceae, accumulate large amounts of silicon. They are sometimes referred to as silicon accumulators. Silicon application to these plants ensures better growth, especially during environmental stress. In the present study, all parameters studied showed positive response to silicon application such as leaf water potential, leaf dry weight, shoot dry weight, root dry weight, total dry weight and shoot to root ratio. Results showed that accumulation of silicon in leaves and roots take place and it was significantly different among cultivars. Transpiration rate per leaf area was significantly affected by the silicon application and growth parameters that is net assimilation rate, relative growth rate and leaf area ratio was also positively affected by the silicon application among cultivars. Water use efficiency was significantly affected by silicon application among sorghum cultivars. It can be concluded that silicon application can enhance growth and development of sorghum and it can be recommended as supplemental fertilizer to enhance drought tolerance. PARC SS-2 has been noted as the drought tolerant sorghum genotype and it must be used to develop future new potential drought combating cultivars.

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