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Foliar Application of Potassium Sulfate Partially Alleviates Pre-anthesis Drought-induced Kernel Abortion in Maize

Ahmad Naeem Shahzad[1*], Ammara Fatima[4], Naeem Sarwar[1], Sajid Bashir[1], Muhammad Rizwan[1], Muhammad Farooq Qayyum[2], Muhammad Kamran Qureshi[3], Muhammad Haseeb Javaid[1] and Shakeel Ahmad[1]
[1]*Department of Agronomy, Bahauddin Zakariya University, Multan-60800, Pakistan*
[2]*Department of Soil Science, Bahauddin Zakariya University, Multan-60800, Pakistan*
[3]*Department of Plant Breeding and Genetics, Bahauddin Zakariya University, Multan-60800, Pakistan*
[4]*Department of Environmental Sciences, Lahore College for Women University Lahore, Pakistan*
[*]For Correspondence: anaeems@gmail.com

Abstract

Reproductive success in cereals is determined primarily by grain setting and grain filling. The kernel abortion in maize during pre-anthesis drought has been widely studied, but the reasons behind this abortion are still largely unknown. The present study investigated the impact of drought stress (control and drought) around pollination and foliar sprays of potassium (K; 0, 1, 2 and 5% K_2SO_4) on leaf K concentrations and yield determinants of maize under greenhouse and field conditions. Results of both experiments revealed that drought stress before pollination strongly reduced the cob fresh weights, number of grains per cob and hence grain yields. While cob length, cob diameter and grain weights were only slightly affected by drought. Potassium concentrations in cob leaves of drought stressed plants were slightly below the critical threshold values. Foliar spray of 2 and 5% K significantly increased the leaf K concentration, number of grains per cob and grain yield in drought treatments of both experiments. Foliar application of K had little or no significant effect on growth and yield determinants of control plants. It is concluded that potassium deficiency could be one factor associated with poor kernel setting under drought stress. Foliar application of 2 and 5% K_2SO_4 before silking can significantly improve grain number and grain yield in drought-stressed maize.

Keywords: Foliar spray; Kernel setting; Maize; Potassium; Pre-anthesis drought

Introduction

Drought affects various physio-biochemical processes of crop growth and development resulting in poor crop yield and productivity. Major growth-limiting factors of drought during vegetative growth are decrease in cell division, expansion and differentiation, leaf expansion and stomatal conductance (Farooq *et al*., 2009). Maize is highly sensitive to soil water deficit which affects mostly all of the agronomic aspects of the crop such as plant height, leaf area, photosynthesis, biomass production and grain yield (Hugh and Richard, 2003; Farooq *et al*., 2009). Most of the research so far has been focused on vegetative growth and later stages of seed development (Wang *et al*., 2009). However, the early stages of seed development particularly pollination and fertilization are so highly sensitive to drought that it may cause a complete crop failure. Water stress during reproductive growth predominantly affects grain setting and therefore severely damages grain yields. In maize, water stresses around pollination aborts the developing kernels by affecting sugar metabolism and assimilate transport (Zinselmeier *et al*., 1995; McLaughlin and Boyer, 2004; Huetsch *et al*., 2015). A decrease in sucrose hydrolysis leads towards sucrose accumulation in source leaves which decreases the sink capacity to support the developing kernels (McLaughlin and Boyer, 2004).

Adjacent to water deficiency itself, plant growth and development is also suppressed with its secondary effects on mineral nutrition. Transportation of mineral nutrients from soil solution to roots and further from roots to shoots depends on the soil moisture status. Low soil moistures restrict root growth and K diffusion rates in the soil and therefore lower the K uptake by roots (Ge *et al*., 2012). Almost 80% of K is taken up by diffusion (Rejado, 1978). Role of K in stomatal movement and control of transpiration is well known. A decrease in transpiration rates under drought stress further reduces the plant's capacity to uptake nutrients (Novak and Vidovic, 2000). Under adverse environmental conditions particularly drought, plant requirement of K is increased (Cakmak and Engels, 1999). Cakmak (2005) suggested that drought-induced stomatal closure causes a decrease in photosynthetic CO_2 fixation

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and an increase in ROS production. Potassium deficiency in drought-stressed plants can further enhance the production of ROS (Mengel and Kirkby, 2001). Therefore, plants growing in drought stress demand higher supplies of K to maintain photosynthetic CO_2 fixation and to decrease the ROS production (Cakmak, 2005).

Potassium (K) is an essential macro nutrient and most of the terrestrial plants cannot survive without potassium (Mengel, 2007). The major functions of K in plant cells include enzyme activation, osmoregulation and charge balancing (Wakeel *et al*., 2011). Adequate supplies of K has shown beneficial effects in maintaining or improving dry mass production, leaf area, water retention, and membrane stability as compared to low K nutrition under drought stress conditions (Wang *et al*., 2013). Similarly, K is essential for cell turgor maintenance via osmotic adjustment (DaCosta and Huang, 2006) and transpiration control via stomatal regulation (Jin *et al*., 2011) under drought stress. In a hydroponic study, external supply of K in the nutrient medium has been shown to improve drought tolerance in wheat cultivars by improving water potential, chlorophyll contents, gas exchange and an effective reactive oxygen species scavenging (Wei *et al*., 2013). Foliar application of K is also shown to improve maize yield under rainfed conditions (Anees *et al*., 2016).

Potassium-deficient plants often exhibit an accumulation of sucrose in source leaves due to poor loading of phloem (Cakmak *et al*., 1994; Zhao *et al*., 2001; Cakmak, 2005). Being the major cation in the phloem, K deficiency can result in poor functioning of the phloem. Keeping in view the involvement of disrupted metabolism and transport of assimilates in drought-induced kernel abortion and the role of potassium in phloem transport of assimilates, the present study was conducted to investigate whether (i) pre-anthesis drought induces K deficiency in source leaves, (ii) foliar application of potassium improves the K status of leaves, and (iii) foliar application of K improves kernel number and grain yield in drought-stressed maize.

Materials and Methods

The research work was conducted at the experimental field and green house of the Department of Agronomy, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University Multan. In this work, one field and one soil pot experiment were conducted. Both experiments were sown on February 23, 2016 and harvested on June 05, 2016.

Field Experiment

A randomized complete block design (RCBD) was laid out with two factors and three replications. Drought treatments included control and drought stress by withdrawing irrigation before pollination. While, potassium treatments included foliar sprays of 0, 1, 2 and 5% K_2SO_4 solutions. Each individual plot contains 6 rows 0.45 m apart with a plot size 3 m * 5 m. Soil samples were collected and analyzed for soil physical and chemical properties. The analysis showed that the soil was silty clay loam having; pH: 8.9, total soluble salts: 0.48%, organic matter: 0.41%, total nitrogen; 0.043%, available phosphorus: 4.81 ppm, potassium: 125 ppm, bulk density: 1.40 g cm^{-3}, EC: 3.72 dS m^{-1}. Nitrogen, phosphorus and potassium were applied at a recommended dose of 150, 100 and 37 kg/ha, respectively. Nitrogen was applied in three splits, while P and K fertilizers were applied at the time of soil preparation. Insects and weeds were controlled adequately throughout the growth cycle of crop. The seeds of hybrid corn (*Zea mays* L. var.45S85) were sown and thinning was done at 4 leaf stage to maintain plant to plant distance of 30 cm. Nine irrigations in total were applied at approx. 10–12 d interval.

Pot Experiment

For this experiment, 8 seeds were sown in soil filled-earthen pots under green house conditions. Pots were filled with 20 kg equal mixture of silt and local soil. Seedlings were thinned to 3 seedlings at 4 leaf stage and to one seedling per pot at 6 leaf stage. Pots were irrigated with 2.5 L nutrient solution at 5 d interval until 45 DAS and later at 2–3 d interval. The composition of nutrient solution was 1 mM $MgSO_4.7\ H_2O$, 1 mM $CaCl_2.2\ H_2O$, 25 uM Fe_2SO_4, 12.5 µM H_3BO_3, 5 µM $MnSO_4.H_2O$, 1 µM $ZnSO_4.7\ H_2O$, 0.25 µM $CuSO_4.5\ H_2O$, and 0.25 µM $(NH_4)_6Mo_7O_{24}.4\ H_2O$. Two gram nitrogen as urea was applied to each pot in three splits.

Application of Treatments

To impose drought stress under field conditions, low soil moisture contents around pollination (from -5 to 3 d of pollination) were achieved by skipping the last irrigation before pollination. In drought treatment, plots were regularly irrigated except for the flowering period (8 d). For this purpose, drought treatment was given when the plants were near silk emergence (at 64 days after sowing) and irrigation was withheld thereafter until 3 d after pollination (83 DAS). The average soil moisture contents from four different locations of drought treatment were 34% on pollination day (80 DAS). In pot experiment, control plants were maintained at 60% water holding capacity (WHC) throughout the growing period by recording weight of each pot. Similarly drought stressed plants were also maintained at 60% WHC until 7 d before pollination. Afterwards, drought stressed plants were maintained at 35% WHC until 3 d after pollination. Drought treatments were immediately irrigated on 3 d after pollination in both experiments. The solutions of K_2SO_4 @ 200 L ha^{-1} at set concentrations were sprayed twice (on 15 and 7 d before pollination) with a hand sprayer to the respective treatments.

Harvest

Ten plants from each plot were randomly tagged for controlled pollination. The ears on tagged plants in both field and pot experiments were covered with brown bags to avoid open pollination. Only one cob (oldest) was maintained on tagged plants by removing the new emerging cobs, if appeared. On day 80 DAS, the tagged cobs were hand-pollinated from fresh pollens (5 d after silk emergence is considered the best time for fertilization in maize (Carcova *et al*., 2000). Fresh pollens were collected from pollen parents separately sown at different intervals to coincide the pollination in different treatments. For hand pollination, pollens were collected in bags by shaking tassels in the bag and bags were inverted on the cob of tagged plant. All the remaining plants in field experiment were left for open pollination. At harvest maturity, tagged plants were harvested and plant height, cob length, cob diameter, cob fresh mass, number of grain rows per cob, number of kernels per cob, 100 grain weight, grain yield and straw yield were determined. Cob leaves (leaf adjacent to cob) were collected and dried at 105ºC for 72 h in a drying oven for analysis of K. Afterwards, 0.5 g of finely ground leaf samples were dry-ashed at 550ºC in a muffle furnace and later dissolved in 2N HCL solution. After making volume, solution was filtered and potassium concentration in was measured by flame photometer.

Statistics

Means ± S.E. were calculated from three replicates in each treatment. Data were subjected to Fischer's analysis of variance using SPSS 18. Multiple comparisons to separate treatment means were performed using the least significant difference (LSD) test with P ≤ 5%.

Results

Drought stress around pollination did not affect plant height under both field and green house conditions (Table 1 and 2). Similarly, K foliar applications also had no effect on plant height in both experiments (Table 1 and 2). Drought had a slight but a significant negative effect on cob length, cob diameter and grain rows per cob under both green house and field conditions. However, K foliar spray at different concentrations had no significant effect on cob length, cob diameter and grain rows per cob under both green house and field conditions. Cob fresh weights were significantly reduced by drought stress under both green house and field conditions.

The most significant drastic effects of pre-anthesis drought were observed in case of number of grains per cob. Drought stress reduced the grain number by almost 50% in 0 K treatments under both controlled and field conditions (Fig. 1). Two foliar sprays of K at different concentrations on -15 and -7 d of pollination had a significant positive effect on grain number in both experiments. In drought treatment, application of 1% K enhanced the grain number by 13% and 12% under green house and field conditions, respectively. However, the mean differences between 0 K and 1% K were not statistically significant. Foliar application of 2% K under drought stress significantly increased the grain number by 31 and 33% under green house and field conditions, respectively. Similarly, 5% K also had a significant positive effect on grain number under drought conditions. On the other hand, K foliar spray at different concentrations did not significantly affect the grain number under both green house and field conditions.

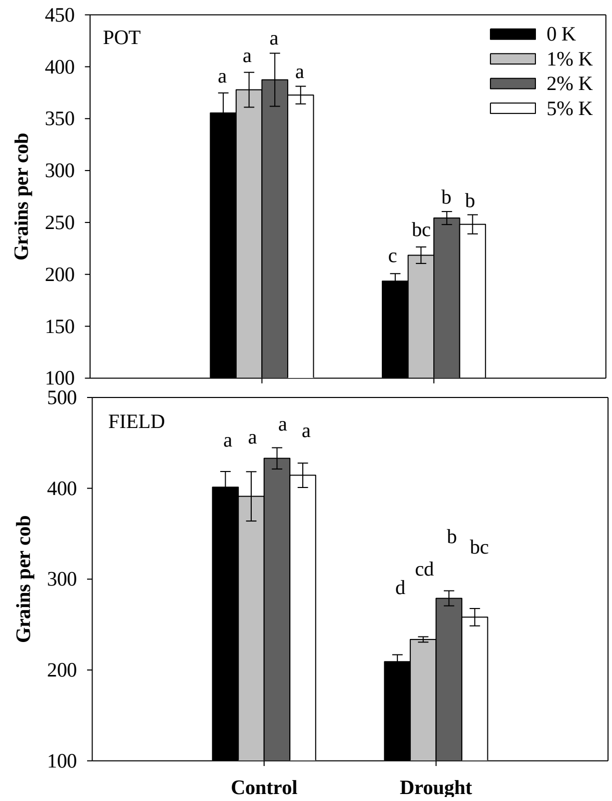

Fig. 1: Effect of pre-anthesis drought and foliar application of potassium at different concentrations on number of grains per cob under green house and field conditions. The bars are mean of three replicates ± S.E. The statistical differences between different treatments are represented by different letters

Pre-anthesis drought slightly but significantly reduced the grain weight under both green house and field conditions (Fig. 2). Foliar application of K at different concentrations had no significant effect on grain weight under both control and drought treatments in the green house experiment. However under field conditions, application of 2% and 5% K slightly increased the grain weight in control plants. While in drought treatment in the field experiment, foliar K had no significant effect on grain weight.

Drought stress significantly reduced the grain yield in both green house and field experiments (Fig. 3). Foliar application of K had no significant effect on grain yield in control plants of both experiments. While, K application @ 2 and 5% significantly enhanced the grain yield as

Table 1: Effect of pre-anthesis drought and foliar application of potassium at different concentrations on plant height and cob growth attributes under greenhouse conditions. The values are mean of three replicates ± S.E. The statistical differences between different treatments are represented by different letters

Treatments	Foliar K (%)	Plant height (cm)	Cob length (cm)	Cob diameter (cm)	Cob fresh weight (g)	Grain rows per cob
Control	0	181.0±7.8 n.s.	21.0±0.7 a	12.4±0.2 a	83.9±6.6 a	14.6±0.8 ab
	1	176.5±9.4	21.1±0.3 a	12.6±0.0 a	85.8±4.0 a	14.7±0.3 ab
	2	181.0±4.2	21.0±0.8 a	12.1±0.5 a	86.2±13.8 a	14.5±1.0 ab
	5	177.5±2.4	20.9±0.3 a	12.0±0.4 a	85.6±3.2 a	15.5±0.4 a
Drought	0	178.7±10.7	16.9±0.4 b	10.4±0.4 b	34.7±5.1 b	12.0±0.9 c
	1	178.0±11.3	17.5±1.2 b	10.2±0.4 b	29.0±3.3 b	12.5±0.7 c
	2	183.0±3.5	17.5±0.3 b	9.9±0.2 b	29.3±1.2 b	10.9±0.2 bc
	5	183.8±1.2	18.3±0.5 b	10.2±0.2 b	32.1±1.1 b	10.9±0.7 c

Table 2: Effect of pre-anthesis drought and foliar application of potassium at different concentrations on plant height, cob growth attributes, straw yield and harvest index under field conditions. The values are mean of three replicates ± S.E. The statistical differences between different treatments are represented by different letters

Treatments	Foliar K (%)	Plant height (cm)	Cob length (cm)	Cob diameter (cm)	Cob fresh weight (g)	Grain rows per cob	Straw yield ($t\ ha^{-1}$)	HI%
Control	0	172.7±9.1 n.s.	23.5±0.8 ab	12.8±0.3 a	87.7±4.5 a	14.2±0.7 abc	12.4±1.8 n.s.	53.7±5.5a
	1	171.8±9.2	24.1±0.2 a	13.6±0.4 a	95.1±2.8 a	15.0±0.3 ab	12.8±1.2	52.0±5.4 a
	2	174.0±4.2	24.9±0.9 a	12.5±0.4 ab	90.8±7.4 a	14.8±1.0 ab	14.1±1.6	50.2±2.9 ab
	5	168.5±2.4	22.8±0.4 abc	12.4±0.5 ab	91.6±3.4 a	15.6±0.4 a	12.4±0.6	58.6±5.3 a
Drought	0	171.7±7.8	18.9±0.8 d	10.3±0.6 bcd	34.7±4.4 b	12.1±1.0 bcd	10.9±1.0	26.7±0.9 c
	1	173.0±9.6	19.9±1.0 d	10.1±0.5 d	30.4±2.8 b	12.1±0.7 bcd	11.0±1.5	27.8±3.3 c
	2	170.3±2.6	20.9±0.5 cd	10.4±0.3 cd	31.4±1.2 b	10.4±0.2 d	12.4±1.4	32.1±2.6 bc
	5	175.1±2.5	21.4±1.0 bcd	10.6±0.3 bcd	34.9±1.2 b	11.3±0.7 cd	12.2±0.6	30.1±1.2 bc

Table 3: Coefficients of correlation (r) among plant height (PH), cob length (CL), cob diameter (CD), cob fresh weight (CFW), number of grain rows (GR), grains per cob (GC), grain yield (GY), 100-grain weight (GW) and cob leaf K concentration (LK) as affected by foliar application of potassium under pre-anthesis drought conditions

Parameters	Pot experiment							
	CL	CD	CFW	GR	GC	GY	GW	LK
PH	-0.468	-0.104	-0.125	0.366	0.100	0.014	0.199	0.135
CL		0.358	0.326	-0.137	0.361	0.222	-0.217	0.287
CD			0.836**	0.389	-0.111	0.018	0.197	-0.233
CFW				0.269	-0.242	-0.102	0.169	-0.187
GR					-0.408	-0.347	-0.094	-0.399
GC						0.827**	0.107	0.788**
GY							0.118	0.751**
GW								0.000
	Field experiment							
	CL	CD	CFW	GR	GC	GY	GW	LK
PH	-0.292	0.170	-0.164	0.318	0.059	-0.099	0.144	0.289
CL		0.498	0.217	-0.040	0.541	0.594*	-0.318	0.480
CD			0.672*	0.475	0.196	0.356	0.091	0.066
CFW				0.418	-0.186	0.136	0.115	-0.206
GR					-0.503	-0.514	-0.040	-0.259
GC						0.806**	-0.003	0.757**
GY							0.033	0.704*
GW								-0.038

* = Significant (P 0.05); ** = Highly significant (P 0.01)

compared to 0 K treatment under drought stress. Both drought stress and K foliar applications did not significantly affect the straw yield under field conditions (Table 2). Drought treatment significantly reduced the harvest index (Table 2) in the field experiment. While, K applications did not significantly alter the harvest index in both control and drought treatments.

Cob leaves were selected as representatives of the source leaves for determination of K concentrations. Analysis showed that drought stress significantly reduced the K concentration in 0 K treatment (Fig. 4). While application of foliar K significantly elevated the K concentration in cob leaves. The correlation data showed that grains per cob and grain yield had a significant positive correlation with cob leaf potassium concentrations in drought-stressed plants of both pot and field experiments (Table 3). Moreover, cob diameter and cob fresh weights were also positively correlated.

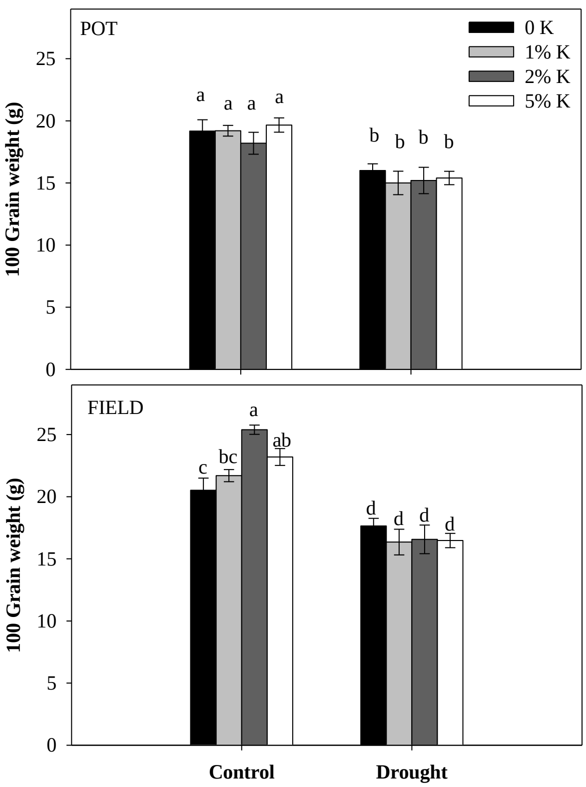

Fig. 2: Effect of pre-anthesis drought and foliar application of potassium at different concentrations on number of grains per cob under green house and field conditions. The bars are mean of three replicates ± S.E. The statistical differences between different treatments are represented by different letters

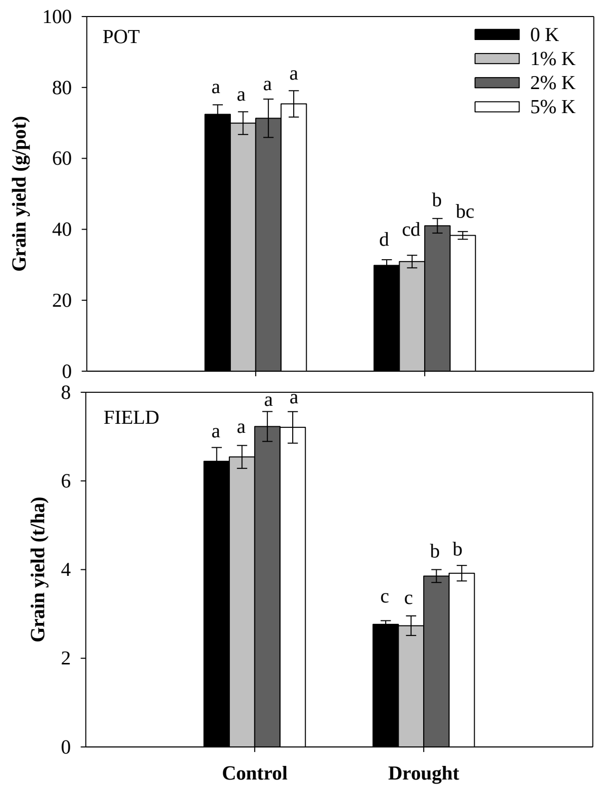

Fig. 3: Effect of pre-anthesis drought and foliar application of potassium at different concentrations on grain yield under green house and field conditions. The bars are mean of three replicates ± S.E. The statistical differences between different treatments are represented by different letters

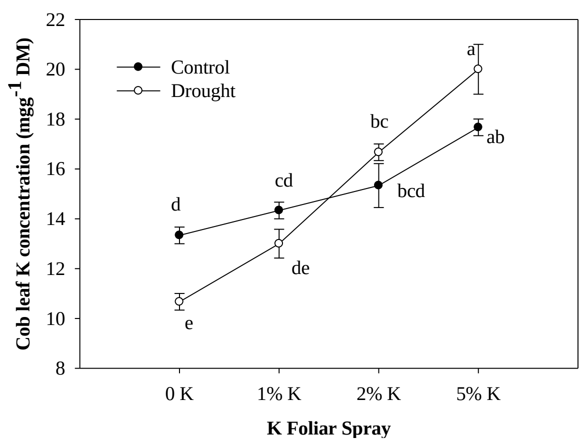

Fig. 4: Effect of pre-anthesis drought and foliar application of potassium at different concentrations on cob leaf K concentration. The values are mean of three replicates ± S.E. The statistical differences between different treatments are represented by different letters

Discussion

Maize sown in spring under field conditions often faces high temperatures and dry weather spells at the time of grain formation and grain filling (Fig. 5). Pre-anthesis drought exposure primarily affects grain number while post-anthesis exposure affects grain weight. Therefore, the present study was conducted to find out the possible involvement of potassium deficiency in maize kernel abortion and the impact of foliar-applied K in improving grain formation during pre-anthesis drought. Results showed that drought stress around pollination severely decreased the number of grains per cob in maize which coincides with a number of similar studies (Zinselmeier *et al*., 1995, 1999; Andersen *et al*., 2002; McLaughlin and Boyer, 2004). The decrease in grain number is generally associated with an accumulation of sugars in source leaves and a poor supply of sugars to developing kernels (Zinselmeier *et al*., 1995, 1999; Heutsch *et al*., 2015). The reduced supply of hexoses to developing kernels starves embryos, which results in the abortion of ovary (Zinselmeier *et al*., 1995; Setter *et al*., 2001). It has been reported that foliar applied K stimulates the export of sugars from phloem (phloem unloading) into the apoplast (Doman and Gieger, 1979). In a recent study, Epron *et al*. (2016) showed that K fertilization-induced increased growth

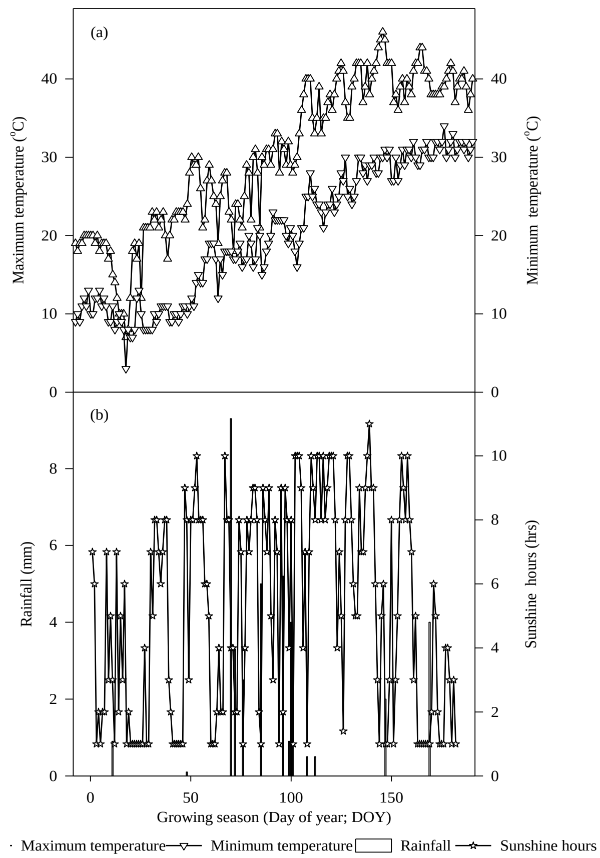

Fig. 5: Daily maximum, minimum temperature (a), sunshine hours and rainfall (b) during the growing season (2016) at Multan, Pakistan

in trees is linked with higher export of assimilates and an increase in volume and speed of phloem transport. Considering the important role of K in phloem transport of assimilates, it was hypothesized that drought stress around pollination may induce K deficiency in source leaves. Maize takes up most of the K by flowering with a peak uptake rates during silking (Rejado, 1978). Leaves adjacent to cobs were selected as a representative of the source tissue to analyze the K status of source tissues. Results showed that the leaf K concentration in control plants (1.33%; Fig. 4) was just at par with the reported critical leaf K values. The critical leaf K values for maize have been shown to be in the range of 1.3 and 1.8% (Rejado, 1978). Drought stress significantly reduced the leaf K (1.06%) indicating an onset of K deficiency in stressed plants.

Foliar application of 2% and 5% K_2SO_4 significantly improved the grain number as compared to 0 K plants under drought treatment. This increase in grain number correlates well with a gradual increase in leaf K concentration upon foliar application of 1, 2 and 5% K_2SO_4 (Table 3). These results suggest that drought-induced K deficiency may be responsible for kernel abortion in maize during pre-anthesis drought. Moreover, an improvement in leaf K status upon foliar application could reduce kernel abortion probably by affecting phloem transport of assimilates. Under optimal conditions the phloem-loaded sucrose is transported to sink organs, however under drought it starts to accumulate in the source leaves, indicating a decline in sucrose utilization by the sink (Hermans *et al*., 2004; Hermans and Verbruggen, 2005). Loading of sucrose into phloem is an active process catalyzed by the proton gradient, established by H^+-ATPase located in the plasma membrane of sieve tube cells (Bouche-Pillon *et al*., 1994; Ward *et al*., 1998). It is well documented that any change in the action of H^+-ATPase would result in a decrease in the export of sucrose into sink (Zhao *et al*., 2000). Moreover, uptake of hexoses by developing kernels from the apoplast is also an active process involving H^+/hexose co transport. It has been suggested by Heutsch *et al*. (2015) that an inhibition of PM H^+-ATPase activity could be responsible for poor delivery of hexoses to developing kernels. As potassium is required for the stimulation of PM H^+-ATPase, its deficiency would disrupt phloem loading of sucrose as well as hexoses delivery to developing kernels. Nevertheless, this proposed phenomenon should be addressed in future studies. However, K-fertilization-induced increase in grain number was only partial and the number of grains per cob were still markedly lower than the control plants, indicating the other factors must also be responsible. The other factors may include abscisic acid (Setter and Para, 2010), ethylene (Yang *et al*., 2007), activities of enzymes invertases and PM H^+-ATPase (Huetsch *et al*., 2015).

In our investigation, grain weight was only slightly reduced by pre-anthesis drought (Fig. 2). This observation coincides with several other evidences (Setter *et al*., 2001; Setter and Para, 2010) who also concluded that water deficit around pollinations only slightly affects the grain size. Potassium treatments had no significant effect on grain weight under both control and drought treatments in the green house experiment. However, application of 2% and 5% K solutions slightly increased the grain weights over 0 K treatment in control plants of the field experiment (Fig. 2). There are earlier reports that K fertilization affects both grain weight and grain number in cereals (Rejado, 1978). This effect of K is more linked with environmental conditions as found in a study that in winter wheat K predominantly affects grain weight, while in spring wheat K affects grain number (Rejado, 1978). Results also show that there was a slight decrease in cob diameter and cob length by drought treatment (Table 1 and 2). On the other hand, cob fresh weights were strongly decreased by drought stress (Table 1 and 2). The lower cob and grain weights could be because of low photosynthetic rates that would reduce the assimilate supply (source-limited; McLaughlin and Boyer, 2004; Hiyane *et al*., 2010). However, Huetsch *et al.* (2014a) argued that accumulation of sugars in the source leaves and maintenance of transpiration rates indicate that a depression in cob growth is not source-limited instead it's the sink strength that is reduced under drought stress. The decreases in grain yield and harvest index by drought stress were more concomitant with decrease in grain number rather than grain weight (Figs. 1–3). Similar trends were observed in case of K treatments where 2 and 5% K solutions significantly improved grain yields in drought treatment. Soil applied K is also shown to improve growth, yield and yield components of maize under drought stress (Maqsood *et al*., 2013).

Conclusion

Exposure of maize crop with drought stress around pollination severely damaged the grain yield by reducing number of grains per cob. Drought-induced K deficiency could be one reason behind this kernel abortion. Foliar application of potassium at silking substantially improved K concentrations in leaves. However, pre-anthesis drought-induced kernel abortion and depression in grain yields were only partially rescued by foliar sprays of potassium.

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