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POTASSIUM OXIDE NANOPARTICLES ALLEVIATE DROUGHT STRESS IN MAIZE IMPACTS ON GROWTH AND YIELD RELATED TRAITS

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Abstract

Drought is a major limit to maize production and reproductive traits are especially sensitive. Potassium helps plants manage water loss. This pot study tested a foliar potassium oxide (K_2O) spray, applied at the flowering stage, on two maize varieties, Sahiwal Gold and Gohar-19. The four treatments were a control, K_2O alone, drought alone and drought with K_2O. Four growth traits and four yield traits were analyzed by analysis of variance and planned contrasts separated the effects of drought and K_2O. Drought lowered stem fresh weight by 58.5%, stem dry weight by 82.3%, grains per cob by 60.7% and cob weight per plant by 49.1%. The K_2O contrast was significant for grains per cob, cob weight per plant and 100 grain weight. Under drought, grains per cob were 72.0% higher with K_2O. K_2O did not significantly change stem weights. Variety effects and interactions were not significant. This study suggests that a K_2O spray at flowering might help grain number under drought. This needs to be tested in the field, with the controls above, before any advice to growers can be given.

1. Introduction

Maize (*Zea mays* L.) is the third most important cereal for global food security, after wheat and rice (Ul-Allah et al., 2020). It is grown widely in dry and semi dry regions, where water is often short. Drought affects maize at almost every stage. It reduces seedling emergence, early growth, photosynthesis, fertilization and seed formation (Kim & Lee, 2023). Water stress also changes growth and biomass partitioning through the growth cycle (Ge et al., 2012). Reported yield losses range from 30 to 90 percent, depending on the stage and on the strength and length of the stress (Sah et al., 2020). The vegetative, silking and ear stages are the most sensitive. Yield losses can reach 25, 50 and 21 percent at these stages (Sah et al., 2020). Water deficit also changes how maize builds its yield. In a field study of twelve maize genotypes, water deficit lowered biomass and grain yield components and kernel number was linked with grain yield under stress (Sathish et al., 2022). Traits that set grain number and grain size are therefore useful to follow when drought is studied. Droughts are also becoming more severe and longer under climate change, which raises the need for practical ways to protect yield (Kim & Lee, 2023).

Potassium is needed for enzyme activity, protein synthesis, osmotic balance and the control of stomata (Hasanuzzaman et al., 2018; Wang et al., 2013). Under drought, it helps plants adapt to water deficit and keep carbon moving from the leaves (Cakmak, 2005; Martineau et al., 2017). Maize responds to potassium in many production systems and grain yield gains have been documented in China (Niu et al., 2011; Wu et al., 2013). Potassium has also been proposed as a route to drought tolerance in maize (Aslam et al., 2013). Soil applied potassium improved yield traits and water productivity of eight maize hybrids and the effect was larger under water stress (Ul-Allah et al., 2020). Potassium was also tested in maize under deficit irrigation in sandy soil (Rusan et al., 2024). An older Egyptian study sprayed potassium as K_2O on maize under three moisture conditions (Abdel-Aziz & El-Bialy, 2004).

Foliar spraying is attractive in dry areas, because dry soil limits nutrient uptake by roots (Amanullah et al., 2016). In pot grown maize, a foliar spray of potassium sulfate at 2 percent gave the best growth and chlorophyll results under severe drought (Wasaya et al., 2021). Foliar nitrogen and potassium also reduced drought effects in sunflower (Hussain et al., 2016). In wheat, potassium sprayed after anthesis was tested for its effect on grain filling under drought (Lv et al., 2017a, 2017b). Nanofertilizers may raise nutrient use efficiency. However, not all nanomaterials are equally safe and their risks must be checked before use (Zulfiqar et al., 2019). Several maize studies used potassium based nano materials against drought. Potassium nano silica reduced the harmful effects of drought stress (Aqaei et al., 2020). Potassium nano silicate was tested on germination under osmotic stress (Weisany et al., 2023). Potassium nano chelate reduced the growth loss caused by water deficit (Dadnia & Zahedi, 2024).

Most of these studies used silicate, chelate or sulfate forms and several worked at the seedling stage. K_2O is a different material. It is a reactive oxide that takes up water readily, so the form that finally reaches the leaf needs care when results are read. In the sources we reviewed, few tested a K_2O spray on maize at flowering under drought. Flowering is a stage when drought can cut seed set and grain number (Sah et al., 2020). A spray at this stage may therefore matter more for grain traits than for early growth.

The aim of this study was to test whether a foliar K_2O spray at the flowering stage could reduce the effects of drought on growth and yield traits of two maize varieties, Sahiwal Gold and Gohar-19, in a pot experiment. We expected the spray to lessen losses under drought. This expectation was framed after the experiment was done, so it is a retrospective hypothesis.

2. Materials and Methods

A pot experiment was conducted in the Botanical Garden of Bahauddin Zakariya University, Multan, Pakistan. Two maize varieties, Sahiwal Gold (V1) and Gohar-19 (V2), were obtained from the Ayub Agricultural Research Institute. Seeds were sown on 8 July 2025 in plastic pots, 26 cm wide, each holding 5 kg of loamy soil. Three plants were kept in each pot. The experiment followed a completely randomized design with two varieties and four treatments. Each combination was replicated three times, giving 24 pots in total. The treatments were T1-control, T2-K_2O alone, T3-drought stress alone and T4-drought stress plus K_2O.

Potassium Oxide (K_2O) was obtained from a commercial source of Potassium Hydroxide (KoH). It was dissolved in distilled water and sprayed onto the leaves during flowering. Field capacity of the soil was checked. Drought stress was induced by limiting irrigation. Control pots received regular irrigation.

The plants were harvested when mature and measurements taken of the appropriate growth and yield variables. The growth variables included: stem fresh weight (g), root length (cm), root dry weight (g) and stem dry weight (g). Dry weights were obtained by putting samples into an oven at 70° C until a constant weight was achieved. The yield variables included: number of cobs per plant, grains per cob, cob weight per plant (g) and 100 grain weight (g). Data was analysed using a two-way ANOVA taking variety and treatment as the variables using R.

3. Results

Treatment had a significant effect on 6 variables out of 8 (Table 1). Stem fresh weight, stem dry

weight, grains per cob, cob weight per plant and 100 grain weight were all affected by treatment ($p<.001$). Number of cobs per plant were also affected by treatment ($p = 0.008$). Root length ($F(3,16) = 3.23$, $p = 0.050$) and root dry weight ($F(3,16) = 2.82$, $p = 0.072$) weren't significant at the 0.05 level. Variety didn't have a significant effect on any of the variables (p values between 0.085 and 0.935). Interaction between variety and treatment wasn't significant for any variables (p values between 0.237 and 0.934). As interactions were small, treatment means were shown for both varieties (Table 2). Variety means can be seen in Table 2 and 3.

Table 1. Analysis of variance for eight traits of two maize varieties (Sahiwal Gold and Gohar-19) under four treatments. SS, sum of squares. MS, mean square. df, degrees of freedom. All values are as reported in the original ANOVA output (Type III sums of squares, 24 pots, total df = 23). The original output prints p as 0.0001, shown here as p < 0.001. Treatment refers to the four treatments T1 to T4 combined.

Trait	Source	df	SS	MS	*F*	*p*
Root length (cm)	Variety	1	2.667	2.667	3.37	0.085
	Treatment	3	7.667	2.556	3.23	0.050
	Variety × treatment	3	0.333	0.111	0.14	0.934
	Error	16	12.667	0.792		
Stem fresh weight (g)	Variety	1	0.043	0.043	0.05	0.831
	Treatment	3	65.221	21.740	24.19	< 0.001
	Variety × treatment	3	0.690	0.230	0.26	0.856
	Error	16	14.381	0.899		
Root dry weight (g)	Variety	1	0.394	0.394	2.28	0.151
	Treatment	3	1.463	0.488	2.82	0.072
	Variety × treatment	3	0.813	0.271	1.57	0.237
	Error	16	2.770	0.173		
Stem dry weight (g)	Variety	1	0.099	0.099	0.16	0.695
	Treatment	3	35.488	11.829	19.14	< 0.001
	Variety × treatment	3	0.322	0.107	0.17	0.913
	Error	16	9.888	0.618		
Cobs per plant	Variety	1	0.167	0.167	0.57	0.461
	Treatment	3	4.833	1.611	5.52	0.008
	Variety × treatment	3	0.167	0.056	0.19	0.901
	Error	16	4.667	0.292		
Grains per cob	Variety	1	104.167	104.167	0.02	0.900
	Treatment	3	648,308	216,103	33.90	< 0.001
	Variety × treatment	3	3,950	1,316	0.21	0.890
	Error	16	101,995	6,375		
Cob weight per plant (g)	Variety	1	888.167	888.167	0.26	0.619
	Treatment	3	173,185	57,728	16.73	< 0.001
	Variety × treatment	3	3,005	1,002	0.29	0.832
	Error	16	55,202	3,450		
100 grain weight (g)	Variety	1	0.042	0.042	0.01	0.935
	Treatment	3	1,549	516.264	84.86	< 0.001

Trait	Source	df	SS	MS	*F*	*p*
	Variety × treatment	3	4.792	1.597	0.26	0.851
	Error	16	97.333	6.083		

Drought had a large effect on stem weight (Figure 1). Stem fresh weight fell from 5.47 g in the control to 2.27 g under drought, a loss of 58.5% (Table 2). Stem dry weight fell from 2.45 g to 0.43 g, a loss of 82.3%. The drought contrast was significant for both traits (stem fresh weight, $F(1, 16) = 70.51$, $p < 0.001$ and stem dry weight, $F(1, 16) = 54.07$, $p < 0.001$; Table 4). Root length and root dry weight were also lower under drought in the means (4.00 against 4.83 cm and 0.25 against 0.69 g). The overall treatment test was not significant for these two traits, so the differences are not interpreted further.

Table 2. Treatment means over both varieties (n = 6 pots), standard error (SE) of a treatment mean and variety means over the four treatments (n = 12 pots). T1, control. T2, K_2O alone. T3, drought alone. T4, drought plus K_2O. All values were recalculated from the original cell means, which were multiplied by 4/3. This correction is inferred and was not verified against raw data (see Materials and Methods). SE is the square root of the error mean square divided by 6. No pairwise tests were run.

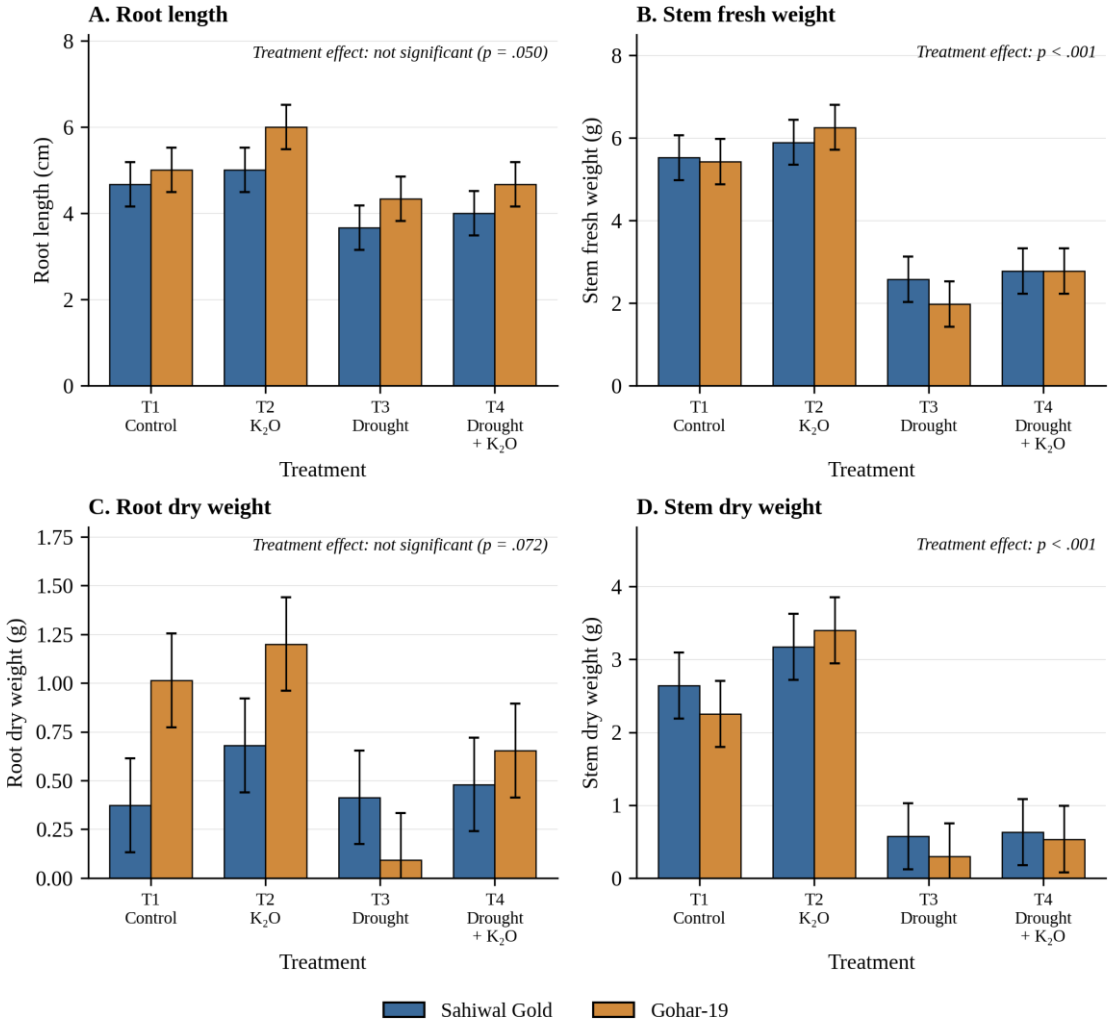
Trait	T1	T2	T3	T4	SE	Sahiwal Gold	Gohar-19
Root length (cm)	4.83	5.50	4.00	4.33	0.36	4.33	5.00
Stem fresh weight (g)	5.47	6.07	2.27	2.77	0.39	4.19	4.11
Root dry weight (g)	0.69	0.94	0.25	0.57	0.17	0.49	0.74
Stem dry weight (g)	2.45	3.29	0.43	0.58	0.32	1.75	1.62
Cobs per plant	1.17	1.50	0.33	0.67	0.22	1.00	0.83
Grains per cob	527	641	207	357	33	431	435
Cob weight per plant (g)	235	333	119	141	24	213	201
100 grain weight (g)	32.3	34.0	15.3	19.5	1.0	25.2	25.3

Table 3. Variety by treatment means (n = 3 pots) and the pooled standard error (SE) of one mean. Treatments and units are as in Table 2 and the values were recalculated in the same way. SE is the square root of the error mean square divided by 3. The 100 grain weight of Sahiwal Gold under T3 is blank in the original data table and its value was taken from the original chart.

Trait	Variety	T1	T2	T3	T4	SE
Root length (cm)	Sahiwal Gold	4.67	5.00	3.67	4.00	0.51
	Gohar-19	5.00	6.00	4.33	4.67	0.51
Stem fresh weight (g)	Sahiwal Gold	5.52	5.89	2.57	2.77	0.55
	Gohar-19	5.43	6.25	1.97	2.77	0.55
Root dry weight (g)	Sahiwal Gold	0.37	0.68	0.41	0.48	0.24
	Gohar-19	1.01	1.20	0.09	0.65	0.24
Stem dry weight (g)	Sahiwal Gold	2.64	3.17	0.57	0.63	0.45
	Gohar-19	2.25	3.40	0.29	0.53	0.45
Cobs per plant	Sahiwal Gold	1.33	1.67	0.33	0.67	0.31
	Gohar-19	1.00	1.33	0.33	0.67	0.31
Grains per cob	Sahiwal Gold	521	659	192	353	46
	Gohar-19	533	623	223	360	46
Cob weight per plant (g)	Sahiwal Gold	240	357	113	143	34

Trait	Variety	T1	T2	T3	T4	SE
	Gohar-19	229	309	125	140	34
100 grain weight (g)	Sahiwal Gold	32.3	34.7	14.9	18.9	1.4
	Gohar-19	32.3	33.3	15.6	20.0	1.4

K_2O did not significantly change stem weights. The K_2O contrast was not significant for stem fresh weight ($F(1, 16) = 2.02$, $p = 0.175$) or for stem dry weight ($F(1, 16) = 2.36$, $p = 0.144$). Under drought, stem fresh weight was 2.77 g with K_2O and 2.27 g without it, which is 22.0% higher. Stem dry weight was 0.58 g with K_2O and 0.43 g without it, which is 33.8% higher. These two differences were not tested as pairs and the K_2O contrast suggests that they could be due to chance. The drought by K_2O interaction was not significant for either stem trait.



Bars show variety × treatment means (n = 3 pots) ± pooled SE from the ANOVA error term.

Figure 1. Growth responses of two maize varieties to four treatments. Panel A, root length (cm). Panel B, stem fresh weight (g). Panel C, root dry weight (g). Panel D, stem dry weight (g). T1, control. T2, K_2O alone. T3, drought alone. T4, drought plus K_2O. Blue bars are Sahiwal Gold and orange bars are Gohar-19. Bars are variety by treatment means (n = 3 pots), recalculated as described in Table 2. Error bars are the pooled standard error of one mean (Table 3), calculated from the ANOVA error mean square and are the same for all bars of a trait. The text in each panel gives the overall treatment p value from Table 1. No pairwise comparisons were tested.

Drought also reduced all four yield traits (Figure 2, Table 2). Cobs per plant dropped from 1.17 to 0.33. Grains per cob dropped from 527 to 207, cob weight per plant from 235 g to 119 g and 100 grain weight from 32.3 g to 15.3 g. These are losses of 71.4, 60.7, 49.1 and 52.7%. The drought contrast was significant for all four traits. It was $F(1, 16) = 14.28$, $p = 0.002$, for cobs per plant and $p < 0.001$ for the other three (Table 4). Among the six traits with a significant treatment effect, stem dry weight lost the most (82.3%) and cob weight per plant lost the least (49.1%).

The K_2O contrast was significant for grains per cob ($F(1, 16) = 16.23$, $p = 0.001$), cob weight per plant ($F(1, 16) = 6.33$, $p = 0.023$) and 100 grain weight ($F(1, 16) = 8.68$, $p = 0.009$). It was not significant for cobs per plant ($F(1, 16) = 2.29$, $p = 0.150$). The interaction was not significant for any yield trait (p from 0.129 to 1.000). There was therefore no evidence that the K_2O effect differed between the two water regimes.

Table 4. Planned contrasts for the six traits with a significant treatment effect. Each F test has 1 and 16 degrees of freedom. The drought contrast compares T3 and T4 with T1 and T2. The K_2O contrast compares T2 and T4 with T1 and T3. The interaction contrast compares T1 and T4 with T2 and T3. The values were recalculated from the means in Table 2 and the error mean square in Table 1.

Trait	Drought F	p	K_2O F	p	Drought × K_2O F	p
Stem fresh weight (g)	70.51	0.001	2.02	0.175	0.02	0.899
Stem dry weight (g)	54.07	0.001	2.36	0.144	1.17	0.296
Cobs per plant	14.28	0.002	2.29	0.150	0.00	1.000
Grains per cob	85.84	0.001	16.23	0.001	0.30	0.588
Cob weight per plant (g)	41.07	0.001	6.33	0.023	2.56	0.129
100 grain weight (g)	245.18	0.001	8.68	0.009	1.50	0.238

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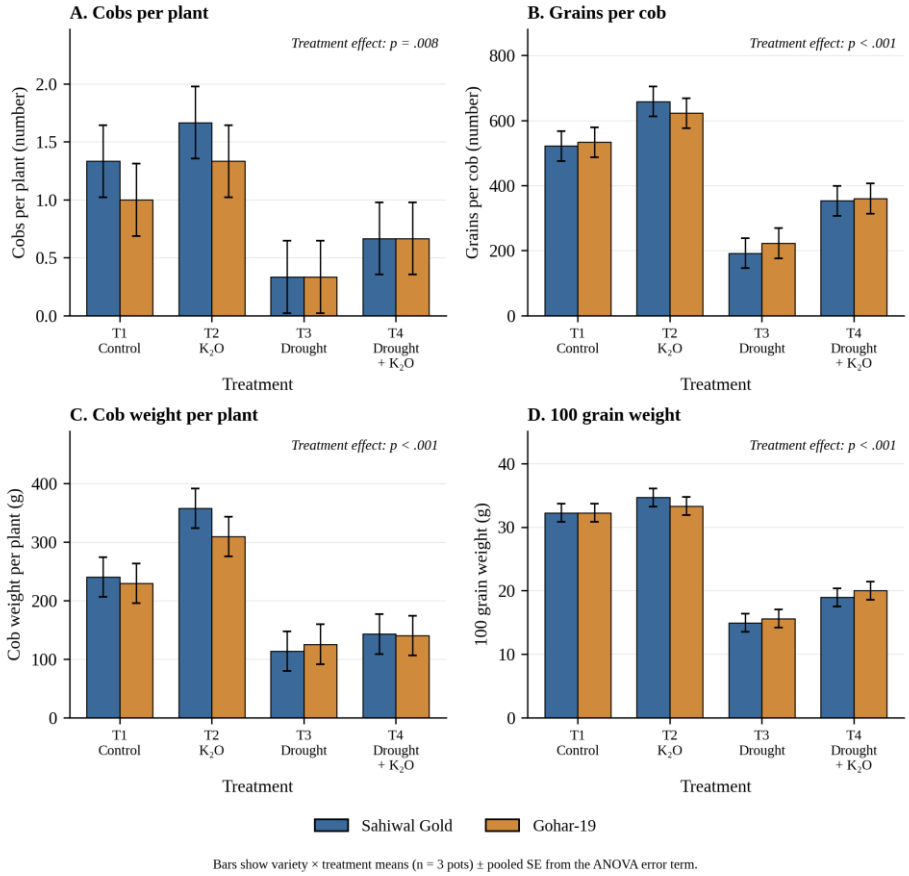


Figure 2. Yield responses of two maize varieties to four treatments. Panel A, cobs per plant. Panel B, grains per cob. Panel C, cob weight per plant (g). Panel D, 100 grain weight (g). Treatments, symbols and error bars are as in Figure 1. Bars are variety by treatment means (n = 3 pots), recalculated as described in Table 2. No pairwise comparisons were tested.

The differences between the K_2O and no K_2O means are given here as descriptions. Without drought, K_2O alone had 641 grains per cob against 527 (21.5% higher) and a cob weight per plant of 333 g against 235 g (42.0% higher). The 100 grain weight was 34.0 g against 32.3 g (5.4% higher) and cobs per plant were 1.50 against 1.17. Under drought, K_2O raised grains per cob from 207 to 357 (72.0%) and 100 grain weight from 15.3 g to 19.5 g (27.5%). Cob weight per plant under drought was 141 g with K_2O and 119 g without it (18.4% higher). Cobs per plant were 0.67 with K_2O and 0.33 without it.

In relative terms, the gains from K_2O were larger under drought than without drought for grains per cob (72.0% against 21.5%) and 100 grain weight (27.5% against 5.4%). The absolute gains were closer. Grains per cob rose by 149 under drought and by 113 without drought and 100 grain weight rose by 4.2 g and 1.7 g. Because the interaction was not significant, the relative differences should be read with care.

K_2O did not bring stressed plants back to control levels. Plants under drought with K_2O (T4) had fewer grains per cob than the control (357 against 527, 32.4% lower). Their cob weight per plant was 141 g against 235 g (39.8% lower) and their 100 grain weight was 19.5 g against 32.3 g (39.7% lower). Cobs per plant were 0.67 against 1.17 (42.9% lower).

All eight traits showed the same order of treatment means, T2 > T1 > T4 > T3. This order held for the two root traits as well, even though their overall tests were not significant. The standard error of a treatment mean was 0.39 g for stem fresh weight, 0.32 g for stem dry weight, 0.22 for cobs per plant, 33 for grains per cob, 24 g for cob weight per plant and 1.0 g for 100 grain weight. The losses caused by drought were many times larger than these errors. The gains from

K_2O under drought were smaller and the largest gains were for grains per cob and 100 grain weight.

The two varieties gave similar results (Table 3, Figures 1 and 2). For the traits with a significant treatment effect, the variety means were close. Sahiwal Gold and Gohar-19 had 431 and 435 grains per cob, 213 g and 201 g cob weight per plant and 25.2 g and 25.3 g 100 grain weight. Root traits showed larger gaps (root dry weight 0.49 g and 0.74 g, $p = .151$), but these were not significant. Both varieties lost grain traits under drought and the interaction tests gave no sign that they responded to K_2O in different ways. With three pots per combination, small differences between varieties could not be detected.

4. Discussion

Drought cut stem growth and grain traits sharply in both varieties. A foliar K_2O spray at flowering was linked with higher grain traits, but it did not return stressed plants to control levels.

The effects of drought agree with earlier work. Large yield losses of maize under drought have been summarized worldwide (Daryanto et al., 2016). Grain number and grain size are set around flowering and grain filling and these stages are very sensitive to water deficit (Kim & Lee, 2023; Sah et al., 2020). Our losses of 49 to 71 percent in the yield traits fall inside the 30 to 90 percent range for yield loss reported by Sah et al. (2020). Water stress has also been shown to change growth and biomass partitioning in summer maize (Ge et al., 2012). In field work with twelve genotypes, kernel number was tied to grain yield under stress (Sathish et al., 2022). Our grain number and 100 grain weight both fell, so both parts of grain yield were affected. The size of the losses depends on the strength and length of the drought. These are not available, so a direct comparison of severity is not possible. Pots also hold little soil, so water deficit can build up faster than in a field.

The K_2O contrast was significant for grains per cob, cob weight per plant and 100 grain weight. Potassium is known to support reproductive development, grain filling and yield under water deficit (Hasanuzzaman et al., 2018). In maize, soil applied potassium improved yield traits and the gain was stronger under water stress (Ul-Allah et al., 2020). Foliar and soil potassium also improved maize growth and yield under moisture stress (Amanullah et al., 2016). Potassium has been proposed as a way to build drought tolerance in maize (Aslam et al., 2013). In pots, foliar potassium sulfate improved growth, leaf water content and chlorophyll of maize under severe drought (Wasaya et al., 2021). Foliar potassium in other crops, including sunflower and wheat, has also been linked to less drought damage and better grain filling (Hussain et al., 2016; Lv et al., 2017a, 2017b). Our grain results point in the same direction. The size of the difference for grains per cob under drought (72 percent) was large, but it came from one season, three pots per combination and one dose.

We did not measure any process that could explain the gain. Published work links potassium with stomatal control, osmotic adjustment, antioxidant activity and the movement of sugars from leaves (Cakmak, 2005; Hasanuzzaman et al., 2018; Martineau et al., 2017; Wang et al., 2013). In cotton, potassium has been linked with better photosynthesis and carbohydrate metabolism under drought (Zahoor et al., 2017). In sunflower, potassium has been linked with the activity of antioxidant enzymes under drought (Soleimanzadeh et al., 2010). These routes could be associated with the grain results here, but they remain untested in our plants. Stomatal opening, leaf water status, sugar levels and potassium content of leaves and grains should be measured in the next experiment.

One result differs from earlier work. Ul-Allah et al. (2020) reported that potassium did not significantly change 1000 grain weight under drought, while the K_2O contrast here was significant for 100 grain weight. The two studies differ in many ways. They used soil applied KCl in the field and we used a foliar K_2O preparation in pots. The stage of application, the dose and the varieties also differ. We cannot say which factor explains the difference.

K_2O did not significantly change stem weights and the two root traits showed no significant treatment effect. This may have a simple reason. The stage at which growth traits were sampled, relative to the spray, is not available. A spray at flowering would have little time to change stem

and root mass if plants were cut soon afterwards. A study with potassium nano chelate found that potassium reduced the growth loss from water deficit after 30 days of treatment (Dadnia & Zahedi, 2024). Potassium has also been reported to improve maize growth under deficit irrigation (Rusan et al., 2024) and a study with potassium nano silica reported fewer harmful effects of drought (Aqaei et al., 2020). Their materials, doses and timing differ from ours, so the results are hard to compare. Low replication also limits our power, because each treatment mean rests on six pots. The root length and root dry weight tests were close to the 0.05 level and a larger experiment could settle them.

The interaction between drought and K_2O was not significant for any trait. The data therefore do not show that K_2O works better under drought than under normal watering. The relative gains were larger under drought, but the absolute gains were similar for the grain traits. Ul-Allah et al. (2020) found a stronger potassium effect under water stress. Our design had little power to detect an interaction, so the question stays open.

The identity of the material is the main weakness. K_2O is a reactive oxide that takes up water readily. The material was dispersed in ethanol and sprayed on leaves, so the compound that reached the leaf may not have been K_2O. It could have been potassium hydroxide, carbonate or simply potassium ions. No tests of crystal phase, particle size or purity are reported. We therefore cannot link the response to nano size and we cannot rule out that the extra potassium alone was associated with it. A bulk potassium salt at the same potassium dose would answer this. A vehicle control with ethanol and PVP is also needed, because both can affect leaves. Only one concentration was tested, so we cannot name the best dose. A very alkaline spray can also injure leaves and this should be checked. These points agree with the warning that not all nanomaterials are equally safe and that their risks must be examined (Zulfiqar et al., 2019).

The study has other limits. It was a pot experiment at one site in one season. No physiological, nutrient or water status traits were measured. In practical terms, the results suggest that a K_2O spray at flowering might help grain number under drought. This needs to be tested in the field, with the controls above, before any advice to growers can be given.

5. Conclusion

Drought strongly lowered stem weights and all grain traits of Sahiwal Gold and Gohar-19 in this pot experiment. A foliar K_2O spray at flowering was linked with higher grains per cob, cob weight per plant and 100 grain weight, as shown by the K_2O contrast. It did not significantly change stem weights or root traits. Plants under drought with K_2O stayed well below the control in grain traits. The two varieties responded in the same way and no interaction was significant. The work shows a partial improvement of grain traits under the tested conditions and does not show drought tolerance.

6. Author's Contribution

K.A. conceived, designed and executed the entire study and collected the experimental data. Z.N. results validation, data visualization and wrote the original draft. M.S.M., A.M., S.A., S.T., and N.W. performed the formal statistical analysis, assisted with experimental maintenance, data curation, and manuscript editing. S.S. supervised the research and reviewed the final manuscript. All authors read and approved the final version.

7. Conflict of Interest

The authors declare no conflict of interest.

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