

Imparting physiological resilience in wheat through potassium-regulated antioxidant adjustments under drought stress

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ABSTRACT

Under changing agroecological conditions, identification of high-yielding genotypes and imparting drought resilience in wheat through physiological adjustments are imperative for sustained wheat productivity and to ensure food security. In this study, different doses of foliar-applied potassium (K), including 2% (8.98 g K per liter of water), 4% (17.96 g K per liter of water), and 6% (26.94 g K per liter of water) using K₂SO₄ (45% elemental K) were tested for growth parameters (length, fresh and dry weights of root and shoot), photosynthetic pigments, and antioxidant (ascorbate peroxidase APX, catalase CAT, peroxidase POD, and superoxide dismutase SOD) responses of promising wheat cultivars (Akbar and Ghazi) during the tillering stage under DS (40% of field capacity). The results revealed that foliar-applied K at 6% concentration was consistently superior, especially for the Akbar cultivar, by recording 75%, 57%, and 50% greater root length, root fresh and dry weights, respectively, than the control. The same combination (Akbar cultivar receiving 6% K) also markedly improved shoot length (42%), fresh weight (31%), and dry weight (66%) compared to the control. Regarding photosynthetic pigments, 6% K improved chlorophyll *a* (93%), chlorophyll *b* (51%), total chlorophyll (66%), and carotenoids compared to the control treatment (no K supplementation), indicating improved photosynthetic efficiency and enhanced plant vitality. Moreover, this treatment also enhanced the activity of APX (77%), CAT (107%), POD (101%), and SOD (43%) in the Akbar cultivar compared to the control. Based on the findings of this study, foliar application of K at 6% concentration may be recommended as a promising strategy to mitigate the deleterious effects of drought by enhancing the biosynthesis of photosynthetic pigments and antioxidants, particularly in drought-tolerant cultivars of wheat.

Keywords: drought ecology, drought resilience, oxidative stress, photosynthetic pigments, reactive oxygen species.

INTRODUCTION

Drought stress (DS) has emerged as a major constraint to the productivity and stability of wheat-based agroecosystems, particularly across water-limited regions of India, Pakistan, Türkiye, Jordan, Saudi Arabia, and Bangladesh, where recurrent water scarcity and changing agroecological

conditions threaten crop performance and food security (Abbas et al., 2023; Iqbal et al., 2023; Wasaya et al., 2025). DS degrades photosynthetic pigments (chlorophyll and carotenoids), restricts the development of root architecture, and impairs nutrient use efficiency (NUE), whereas antioxidant hyperactivity reflects the adaptive response of crop plants (Ahmad et al., 2018; Sharma et al., 2022; Attiq et

al., 2024; Ahmad et al., 2025; Takács et al., 2025; Akhter et al., 2025). In response to DS, plants triggered the biosynthesis of antioxidants (ascorbate, glutathione, etc.) and enzymatic antioxidants like superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which scavenged reactive oxygen species (ROS) and mitigated oxidative damage (Hasanuzzaman et al., 2020). Moreover, these antioxidants preserved cellular redox homeostasis and safeguarded essential cellular constituents against oxidative stress (Kirova et al., 2022). Collectively, these insights underscore the significance of promoting a robust antioxidant-based defense system in wheat for alleviating the adverse effects of DS. Wheat has been regarded as a strategic crop to ensure the food security and economic stability of over half of the world's population (Ding et al., 2025; Lamom et al., 2025; Li et al., 2025), which requires increasing its yield on a sustainable basis (Rehman et al., 2020). Along with yield reduction, DS also negatively affected the nutritional profile (including carbohydrates, protein, and essential nutrients) of wheat grains and a variety of wheat-flour products, including bread, pasta, breakfast cereals, and pastries, which form a significant part of humans' diets (Aurangzaib et al., 2022).

Recently, potassium (K) application as a foliar spray has been shown to significantly boost vegetative growth of crop plants by improving the biosynthesis of photosynthetic pigments and antioxidants under DS. The maintenance of plant metabolism and adjustment of stress responses of plants under water-limited conditions have been attributed to exogenously applied K (Waraich et al., 2020). Consistently, K improved chlorophyll biosynthesis, contributing to the efficient capture of photosynthetically active radiation (PAR), which triggered the process of photosynthesis in water-scarce conditions (Ahmad et al., 2025). Moreover, K served as a cofactor for the biosynthesis of various enzymes involved in antioxidant defense mechanisms, which mitigated oxidative damage (Ahmad et al., 2019). Ali et al. (2021) also revealed that foliar-applied K improved leaf pigments (chlorophyll *a*, chlorophyll *b*, and carotenoids) in drought-stressed wheat plants, preventing the suppression of photosynthesis rate by enhancing light absorption efficiency. In addition, foliar-applied K also enhanced the antioxidant defense system in wheat plants subjected to drought by increasing the activity of antioxidant enzymes, such as SOD, CAT, and POD (Ahmad et al., 2021). Consistent with these findings, antioxidant

enzymes were reported to scavenge ROS along with reducing oxidative stress in plants (Meena et al., 2022). The K suppressed the release of surplus electrons to oxygen, which tends to react with proteins, lipids, and membranes, causing oxidative damage to cell organelles (chloroplasts, mitochondria, and nucleic acids), altered membrane potential, and deactivated the normal functions of metabolic enzymes, leading to programmed cell death (Akhtar et al., 2022). Moreover, DS primarily reduced osmotic potential, relative water content, leaf water potential, and leaf turgor potential along with leaf diffusive resistance, which led to decreased leaf transpiration rate (Ahmad et al., 2025). Likewise, K effectively mitigated the deleterious impacts of DS, including cell membrane permeability, transpiration flux, and active transport, thereby improving nutrient mobilization within plant tissues by activating ascorbate peroxidase (APX) (Anees et al., 2016). Critically, K improved DS damage related to the photosynthetic apparatus and prevented the disruption of enzyme activity, such as Rubisco, during the Calvin cycle. This decrease in the fixation of atmospheric carbon into organic products ultimately reduces grain yield (Ghazi et al., 2021).

Notwithstanding a substantial number of previous studies, significant research gaps exist in sorting out optimal K doses owing to lower foliar K uptake under DS, with less than 50% absorption rate reported at low concentrations, a limitation primarily attributed to DS-induced cuticular thickening restricting K entry into the tissues of leaves, thereby necessitating testing higher K concentrations. Moreover, results reported in previous studies have been variety-specific and confined to specific pedo-climatic conditions, raising the need to perform further studies for developing research-based recommendations applicable to broader perspectives. Therefore, we hypothesized that foliar-applied K at an appropriate concentration may ameliorate DS-induced adverse effects by enhancing growth parameters, maintaining photosynthetic pigment stability, and strengthening antioxidant-based defense mechanisms in promising wheat cultivars. Thus, the objective of this study was to examine the deleterious impacts of drought stress and the drought ameliorative effects of different doses of foliar-applied potassium on the morphology, photosynthetic pigments, antioxidants, and overall growth performance of selected wheat cultivars up to the tillering stage.

MATERIALS AND METHODS

Experimental locality and treatment details

A trial was conducted at the wire-house of the Department of Botany, University of Central Punjab, Constituent College, Bahawalpur (29°23'44"N 71°41'1"E, having an altitude of 118 m), Pakistan, during 2024 and 2025. The experiment evaluated the impact of different doses of foliar K (control, 2%, 4%, and 6%) applied on the tillering stage of two promising wheat varieties (Akbar and Ghazi) under 100% of the field capacity (FC) and DS conditions (40% of the FC). Three different concentrations of foliar K (w/v) were used, including 2% (8.98 g K per liter of water), 4% (17.96 g K per liter of water), and 6% (26.94 g K per liter of water), using K_2SO_4 (45% elemental K) by following the procedure of Waraich et al. (2020). Commercial potassium fertilizer (K_2SO_4) was diluted in deionized (DI) water to prepare these concentrations under study. The seeds of wheat cultivars were acquired from the Regional Agriculture Research Institute (RARI), Bahawalpur, Punjab province, Pakistan. The tested wheat cultivars (Akbar and Ghazi) are drought-tolerant with vigorous growth traits (particularly robust vegetative growth and superior tillering capacity), a proliferous root network, and high yield potential under stressful conditions (Ahmad et al. 2022). The trial was performed by employing a completely randomized design (CRD) with a three-factor (K doses, levels of DS, and wheat cultivars) factorial arrangement. All the treatments were maintained in three replications, and the whole trial was repeated to ensure more reliable and highly validated data of response variables. Seeds of wheat cultivars were sown in pots containing a standardized soil mixture. At the tillering stage, the foliar K was applied uniformly using a hand-held sprayer with the aim of supplying ample K to the plants through their leaves. To induce DS conditions, 40% of the FC was maintained along with the control (100% of the FC), whereas the gravimetric method was used to estimate the FC as suggested by Ahmad et al. (2025). Agronomic yield-contributing traits of wheat cultivars were recorded by following the standard procedures as reported by Ahmad et al. (2025).

Assays for leaf photosynthetic pigments

The pigments involved in the photosynthesis process, such as carotenoids and chlorophyll (*a*

and *b*) of wheat leaves, were measured with the help of a spectrophotometer (HACH DR6000, Hach Lange, Germany), by setting its wavelength specific for each photosynthetic pigment. Chlorophyll *a* and chlorophyll *b* were recorded to have distinct absorption peaks in the red and blue regions of the spectrum, while carotenoids absorbed light in the blue and green regions. Then, wheat leaves were subjected to a pigment extraction process involving grinding wheat leaves into a homogeneous paste by mixing the solvents of acetone and methanol. To prevent pigment degradation, the extraction procedure was performed in complete darkness. Thereafter, debris and insoluble particles were removed by subjecting the extracted pigment solution to centrifugation. After that, the supernatant was transferred to quartz cuvettes suitable for spectrophotometric analysis. By comparing the absorbance readings to calibration curves generated from standard pigment solutions, pigment content in the leaf samples of wheat plants was recorded Wellburn (1994).

Antioxidants assay

The estimation of different antioxidants (APX, CAT, POD, and SOD) in wheat leaves was performed as per the suggested protocols. To determine the activity of APX, a reaction mixture (50 mM phosphate buffer and 1 mL of the sample) having a pH of 7.6 was prepared. In this reaction mixture, further addition of ascorbic acid (0.25 mM), Na EDTA (0.1 mM), and H_2SO_4 (12 mM) was done, whereas ascorbic acid absorbance reduction at a wavelength of 290 nm was monitored (Cakmak et al., 1994). In addition, the activity of CAT was assessed by estimating the decomposition rate of hydrogen peroxide (H_2O_2) into molecules of water and oxygen. The sample solution, comprising 3 mL, consisted of 50 mM phosphate buffer with a neutral pH of 7.0. To this solution, 5.9 mM H_2O_2 and 0.1 mL of enzyme extract were added. The changes in absorbance at 240 nm were recorded using a spectrophotometer (HACH DR6000, Hach Lange, Germany), indicating the consumption of H_2O_2 over time intervals of every minute Aebi (1984).

Moreover, to estimate the activity of POD, a reaction solution having 5.0 pH was prepared by mixing phosphate buffer (50 mM), guaiacol (20 mM), and H_2O_2 (40 mM), whereas an enzyme extract (0.1 mL) was also added. After an interval of twenty seconds, the absorbance increment

was recorded at the wavelength of 470 nm, which indicated tetraguaicol formation. A single unit of enzyme caused a 0.01 increment in the optical density (OD) within 1 minute (Chance and Maehly 1955). Furthermore, SOD biosynthesis was also estimated by using an N2 solution for the preparation of plant samples. The ground plant material was then mixed uniformly with a phosphate buffer having 7.6 pH. The resulting mixture was subjected to the SOD assay, and the activity of SOD was estimated accordingly (Giannopolitis and Ries, 1977).

Statistical analysis

The mean data were statistically analyzed by employing the three-way analysis of variance (ANOVA) method using Statistix 8.1 software. The purpose of this analysis was to determine the significance of the observed effects in the data. Moreover, to assess the significance level among treatment means, the least significant difference (LSD) test was used at significance levels of $\alpha = 0.05$, whereas statistical significance was denoted as $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$ (Steel and Torrie, 1962).

RESULTS AND DISCUSSION

Above- and below-ground growth attributes

The results indicated a decrease in growth attributes of wheat varieties (Akbar and Ghazi) when exposed to DS; however, the impact of different doses of foliar-applied K and varieties remained highly significant (Table 1). It was noted that compared to normal conditions (100% of FC), DS significantly reduced the above- and below-ground growth traits of both wheat cultivars, irrespective of K doses. However, K foliar application in 6% concentration remained superior to the rest of the K doses under normal and DS conditions (Figure 1). Notably, the Akbar cultivar outperformed Ghazi in terms of growth attributes under both DS and control conditions. Overall, K foliar application in 6% concentration (26.94 g K per liter of water) effectively mitigated the deleterious effects of DS in both cultivars. However, the Akbar cultivar responded more vigorously to K application by recording 75%, 57%, and 50% greater root length, root fresh and dry

weights, respectively, than plants of the same cultivar receiving no K sprays under DS conditions. Along with root development, 6% K supplementation remained effective in significantly boosting the length (42%) as well as fresh (31%) and dry (66%) weights of the shoots compared to the control treatment, especially in the case of the Akbar cultivar under DS conditions (Figure 2). The highest dose of K also remained effective in improving the length and fresh and dry weights of root (71%, 45%, and 44%, respectively) and shoot (36%, 33%, and 69%, respectively) of the Ghazi cultivar when exposed to DS in comparison to control treatment (no K supplementation); however, this ameliorative impact of K was less pronounced than in the Akbar cultivar. Overall, the lowest dose of K was also effective in ameliorating the adverse effects of DS, while increasing the dose of K recorded a corresponding increment in the above- and below-ground growth traits of both cultivars under investigation.

These findings suggest that the drought-tolerant cultivar Akbar developed comparatively more prolific and deeper root systems, as indicated by greater root length as well as their fresh and dry weights, likely by virtue of its superior genetic potential, enabling plants to extract moisture from deeper soil. These findings agreed with previous reports, whereby drought tolerance in wheat was reported to be strongly associated with vigorous root system development, leading to enhanced capacity of wheat plants to absorb soil water under DS conditions (Akhter et al., 2025; Iqbal et al., 2023). Additionally, cultivars producing deeper and vigorously branched root systems were able to sustain water uptake, leading to a well-maintained leaf water potential, delaying dehydration-induced stomatal closure, and supporting the photosynthetic process during spells of surface soil drying. Besides root length, significantly higher root biomass (fresh and dry weights) facilitated the acquisition of nutrients under DS, which indirectly supported the metabolic activities and vigorous vegetative growth in wheat plants exposed to water scarcity (Takács et al., 2025; Sharma et al., 2022).

In this experiment, various doses of foliar-applied K (particularly 6% concentration) alleviated DS-induced inhibition of shoot length, and its fresh and dry weights, probably by enhancing the proliferation of roots, which improved the uptake of moisture from deeper soil horizons, maintained osmotic adjustment, stomatal regulation, photosynthetic stability, and ultimately

made wheat plants resilient to DS. These findings aligned with the conclusions forwarded by previous studies, whereby foliar-applied K imparted a strong drought-alleviating influence on underground and aboveground parameters of wheat (Wang et al., 2013). Similar to our findings, K foliar supplementation was reported to ameliorate the DS-induced negative effects by reinforcing the growth of roots and shoots, which contributed to strengthening plants' adaptability to a shortage of water. Moreover, on exposure to DS, exogenous K supplementation (2% w/v K_2SO_4) proved its efficacy by enhancing shoot growth and maintaining turgor pressure in the leaves under severe DS, underscoring K concentration-dependent responses of plants (Wang et al., 2021; Wasaya et al., 2021; Ahmad et al., 2018).

Photosynthetic pigments

The recorded findings were highly significant regarding the deleterious impact of imposed DS, the ameliorative effect of K supplementation, and the differential response of wheat cultivars (Akbar and Ghazi) to different doses of K in terms of photosynthetic pigments (Table 1). The DS decreased chlorophyll pigments compared to the control group, reduced photosynthetic activity, and reduced plant vigor. However, foliar K in all tested concentrations (2%, 4%, and 6%)

demonstrated positive impacts on photosynthetic pigments of both cultivars under investigation under normal and DS conditions (Figure 3). Among tested doses of K, 6% concentration (26.94 g K per liter of water) outperformed rest of treatments by causing significant increments in chlorophyll *a* (93%), chlorophyll *b* (51%), and total chlorophyll (66%) contents than the control treatment (no K supplementation), suggesting improved photosynthetic efficiency and plant vitality. In addition, the same dose of K improved carotenoid biosynthesis (59%) in the Akbar cultivar compared to the control treatment. However, the most performing combination (Akbar cultivar receiving 6% dose of K) recorded markedly reduced chlorophyll *a* (91%), chlorophyll *b* (38%), total chlorophyll (61%), and carotenoid content (39%) compared to the corresponding values recorded by the same cultivar under normal conditions (100% of FC). Moreover, wheat variety comparison revealed that Akbar produced significantly higher photosynthetic pigments than Ghazi, regardless of foliar-applied K concentrations, indicating Akbar was significantly more resilient to DS as indicated by a higher capacity to synthesize chlorophyll under water-limited conditions.

Under DS, photosynthetic pigments (particularly chlorophyll) maintain vegetative growth by enhancing the interception of PAR and C-assimilation during photosynthesis. Primarily, the DS

Table 1. Analysis of variance (ANOVA) for growth parameters of wheat cultivars under different potassium levels and drought stress conditions

Parameters	Treatments (T)	Variety (V)	Drought stress (DS)	T x V	T x DS	V x DS
RL	**	**	**	***	***	**
RFW	**	***	**	**	**	***
RD	**	***	**	***	***	**
SL	***	**	*	**	**	**
SFW	**	***	**	**	**	**
SDW	**	**	**	**	**	*
Chl <i>a</i>	***	**	**	**	*	**
Chl <i>b</i>	***	**	**	**	**	***
Total Chl	**	*	***	***	**	**
Carotenoid	***	**	**	***	**	***
Ascorbate peroxidase	**	**	**	***	***	**
Catalase	**	**	*	**	**	**
Peroxidase	**	***	***	***	**	**
Superoxide dismutase	*	**	**	*	***	**

Note: N.S – Non-significant, *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$. RL– root length, RFW– root fresh weight, RDW– root dry weight, SL– shoot length, SFW– shoot fresh weight, SDW– shoot dry weight, Chl– chlorophyll.

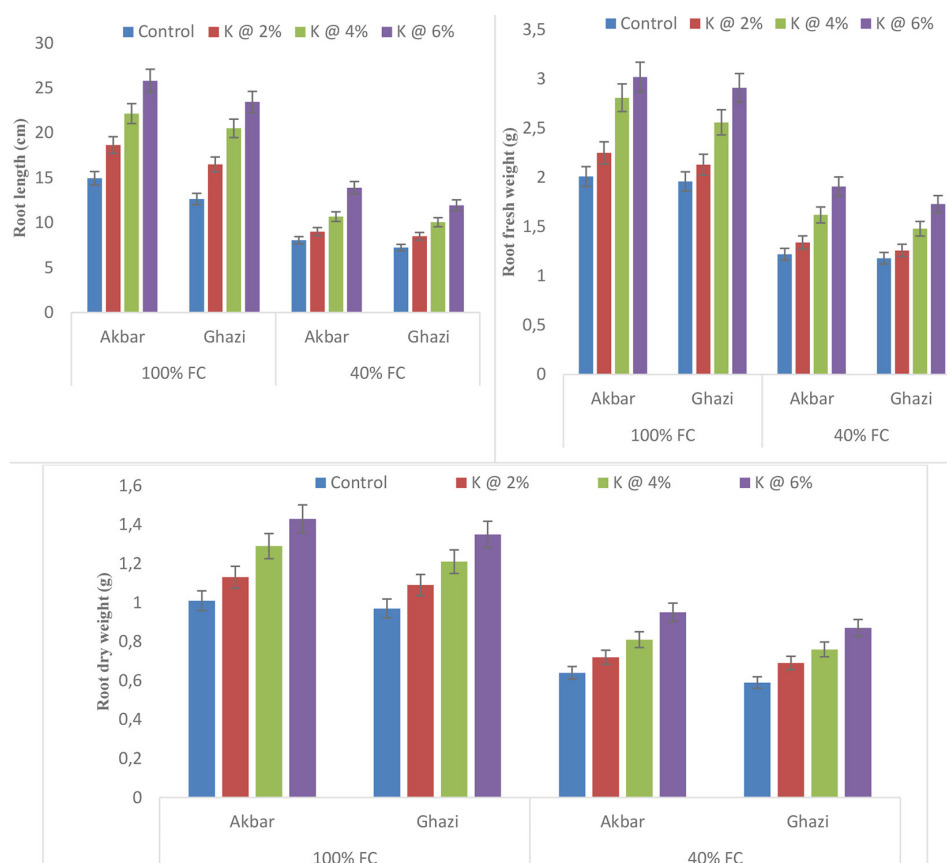


Figure 1. Foliar-applied potassium effects on below-ground growth attributes (length, fresh weight, and dry weight of roots) of wheat cultivars under normal and drought stress conditions (bars represent means $\pm$ standard deviation of three independent replicates)

severely restricted photosynthesis through chlorophyll degradation by initiating chlorophyllase activity, which also caused oxidative damage to the membranes of the chloroplast. Therefore, improving the biosynthesis of chlorophyll necessarily serves as a vital adaptive response of crop plants for achieving resilience against water shortage. We recorded that foliage-applied K counteracted the DS-induced decline in chlorophyll by enhancing the biosynthesis of chlorophyll *a*, chlorophyll *b*, as well as total chlorophyll in selected wheat cultivars, whereas the Akbar cultivar responded vigorously to K application. It may be interpreted that under imposed DS (40% of FC), exogenous K application at 6% concentration effectively protected the photosynthetic apparatus by maintaining its integrity and functionality. The K supplementation preserved chlorophyll under abiotic stressors by regulating leaf water status and stomatal conductance (Hawkesford et al., 2023; Gu et al., 2021). Additionally, K optimized stomatal regulation, prevented moisture loss, and enhanced CO₂ diffusion, thereby

suppressing photo-transpiration. Moreover, K remained instrumental in activating various enzymes involved in the biosynthesis of chlorophyll and energy metabolism, facilitating the preservation of total chlorophyll under DS (Artyszak et al., 2021; Farzane et al., 2021).

Besides chlorophyll, carotenoids tend to safeguard the photosynthetic apparatus against DS-induced oxidative and photochemical damage in wheat. They mitigated the deleterious effects of DS by serving as potential scavengers of free radicals and thus limiting the oxidative damage to chlorophyll and photosystem II (Iqbal et al., 2023; Munsif et al., 2022a). In this study, carotenoid content was significantly reduced under DS, and the highest dose of foliar-applied K improved its content, especially in the Akbar cultivar. Previously, it has been reported that K-driven improvements in carotenoid content contributed to photoprotection through non-photochemical quenching (NPQ) and assisted in dissipating excessive absorbed light energy as heat under water-limited conditions (Slaman et al., 2025; Safina et al., 2025; Munsif et al., 2022b).

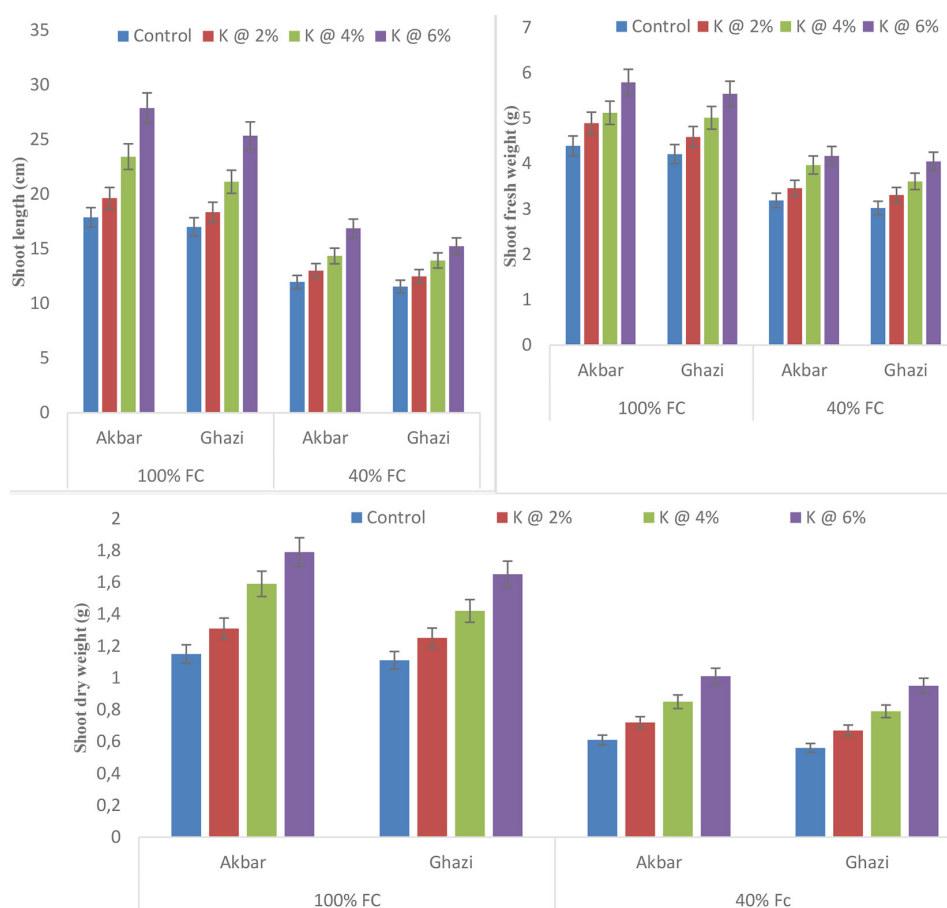


Figure 2. Foliar-applied potassium effects on above-ground growth attributes (length, fresh weight, and dry weight of shoot) of wheat cultivars under normal and drought stress conditions (bars represent means $\pm$ standard deviation of three independent replicates)

In addition, K supplementation was reported to increase carotenoid content, which facilitated the retention of chlorophyll under DS and, more importantly, contributed significantly to delaying the process of leaf senescence (Salman et al., 2025). Similar to our findings, it has been reported that foliage-applied K in different doses promoted the accumulation of carotenoids through strengthening metabolic and photosynthetic stability, along with reducing oxidative damage to chloroplasts in wheat during spells of water shortage. Moreover, sufficient K supplementation triggered the synthesis of ATP and facilitated the continuation of carbohydrate metabolism, leading to the provision of the required energy and carbon skeletons for the biosynthesis of carotenoids, while K deficiency caused a significant reduction in carotenoid content under DS (Safina et al., 2025). Furthermore, K-mediated improvement in carotenoid biosynthesis promoted ABA production and activated the stress signaling mechanism, contributing to drought adaptation in wheat (Munsif et al., 2022b).

Antioxidant activity

It was recorded that DS and K supplementation produced pronounced differential responses of wheat cultivars in terms of biosynthesis of antioxidants (APX, CAT, POD, and SOD) (Table 1). The results pertaining to the antioxidant assay revealed that DS imparted adverse impacts on the activity of different antioxidants in both wheat varieties (Akbar and Ghazi), compared to the control condition (100% of FC) (Figure 4 and 5). It was noted that the Akbar cultivar recorded markedly higher content of all antioxidants than Ghazi under DS, indicating a more robust antioxidant defense system. The exogenous K supplementation in various concentrations (2%, 4%, and 6%) remained effective in mitigating the deleterious effects of DS in wheat plants. In particular, foliar-applied K in 6% concentration (26.94 g K per liter of water) improved APX (77%), CAT (107%), POD (101%), and SOD (43%) activity in the Akbar cultivar in comparison to the control treatment (no K supplementation)

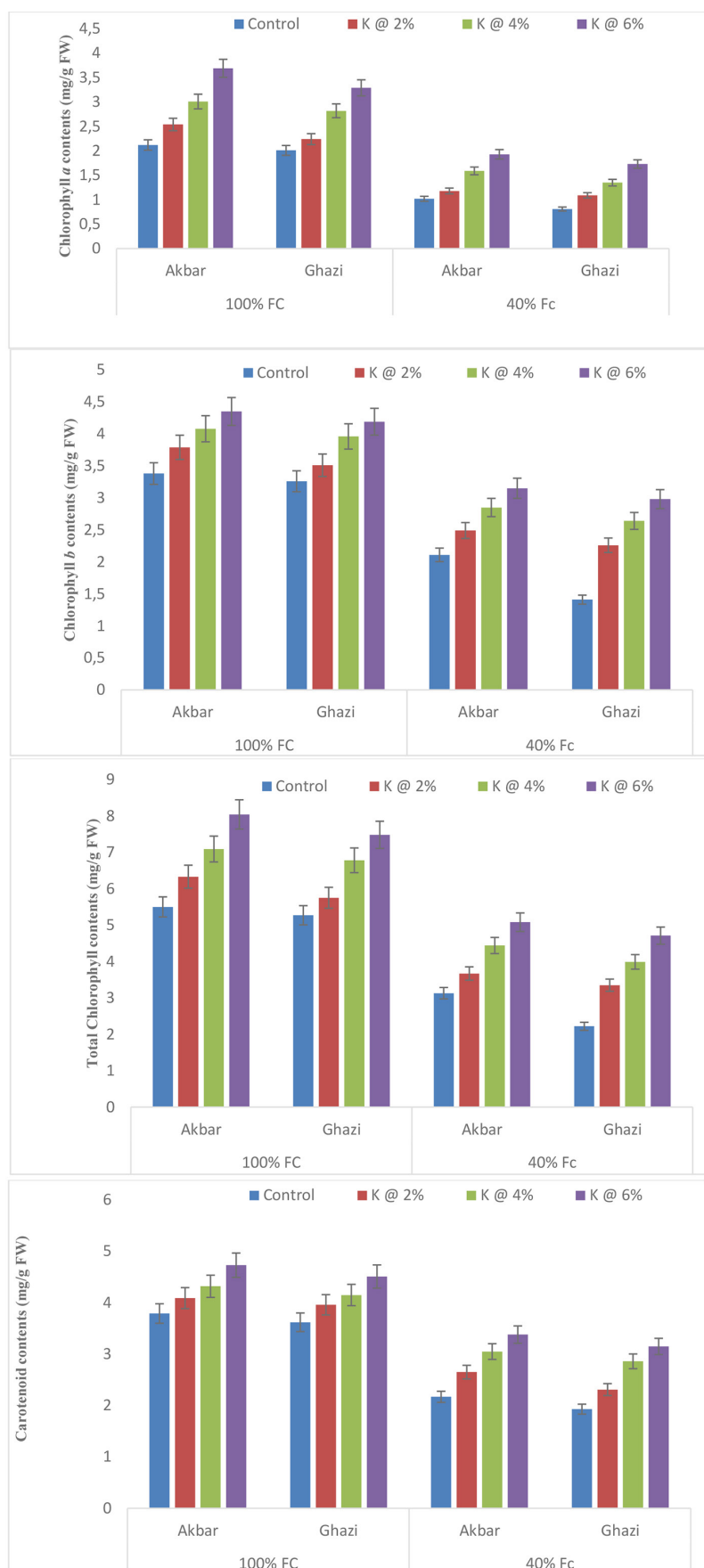


Figure 3. Foliar-applied potassium effects on photosynthetic pigments (chlorophyll a, chlorophyll b, total chlorophyll, as well as carotenoid in wheat cultivars under normal and drought stress conditions (bars represent means $\pm$ standard deviation of three independent replicates)

under DS conditions (Figure 4 and 5). Moreover, the corresponding increments in APX, CAT, POD, and SOD activity in the Ghazi cultivar were 133%, 114%, 75%, and 38%, respectively, in comparison to the control treatment (no K supplementation) under DS conditions.

Under DS, ROS accumulate owing to restricted assimilation of CO₂, disruption of the electron transport chain, and photorespiration (Sulaman et al., 2025). A serious oxidative damage to vital proteins, lipids, nucleic acids, and cellular membranes is caused by ROS, such as superoxide radicals (O₂⁻), hydrogen peroxide (H₂O₂), and hydroxyl radicals (OH) (Farzane et al., 2021). To offset these deleterious impacts of oxidative stress, wheat plants need a robust antioxidant defense system involving APX, CAT, POD, and SOD. Under DS, both APX and CAT performed different functions complementarily to initiate the detoxification process of H₂O₂. Interestingly, APX effectively captured low-level H₂O₂ from chloroplasts and CAT rapidly removed it into peroxisomes and

thus protected cells from oxidative damage (Ahmad et al., 2018). In our study, the maximum dose (6%) of foliage-applied K significantly improved the activity of APX and CAT. Similar to our findings, it was reported that exogenously applied K improved the activity of CAT, which converted H₂O₂ into water and oxygen, providing a robust defense against ROS accumulated under drought. Moreover, APX was reported to handle low levels of H₂O₂, while CAT removed high concentrations of H₂O₂ and thus maintained a vigorous mechanism of ROS homeostasis, which prevented lipid peroxidation (El-Metwally et al., 2025). Furthermore, it has been reported that foliar application of K played a key role in APX and CAT gene upregulation (significantly enhanced expression resulting in higher biosynthesis and activity under DS), which efficiently scavenged ROS and imparted drought tolerance in wheat. The foliar-applied K multiplied the generation of metabolic energy (ATP) and reduced NADPH, which led to ascorbate regeneration. This directly stimulated

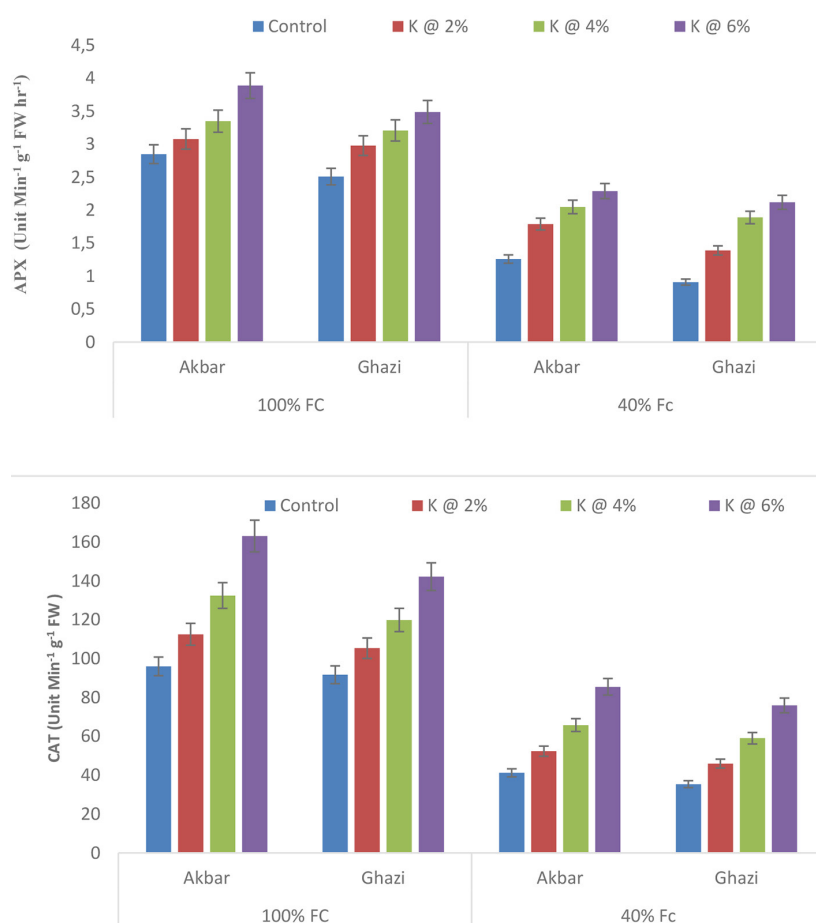


Figure 4. Foliar-applied potassium effects on ascorbic peroxidase (APX) and catalase (CAT) activity in wheat cultivars under normal and drought stress conditions (bars represent means $\pm$ standard deviation of three independent replicates)

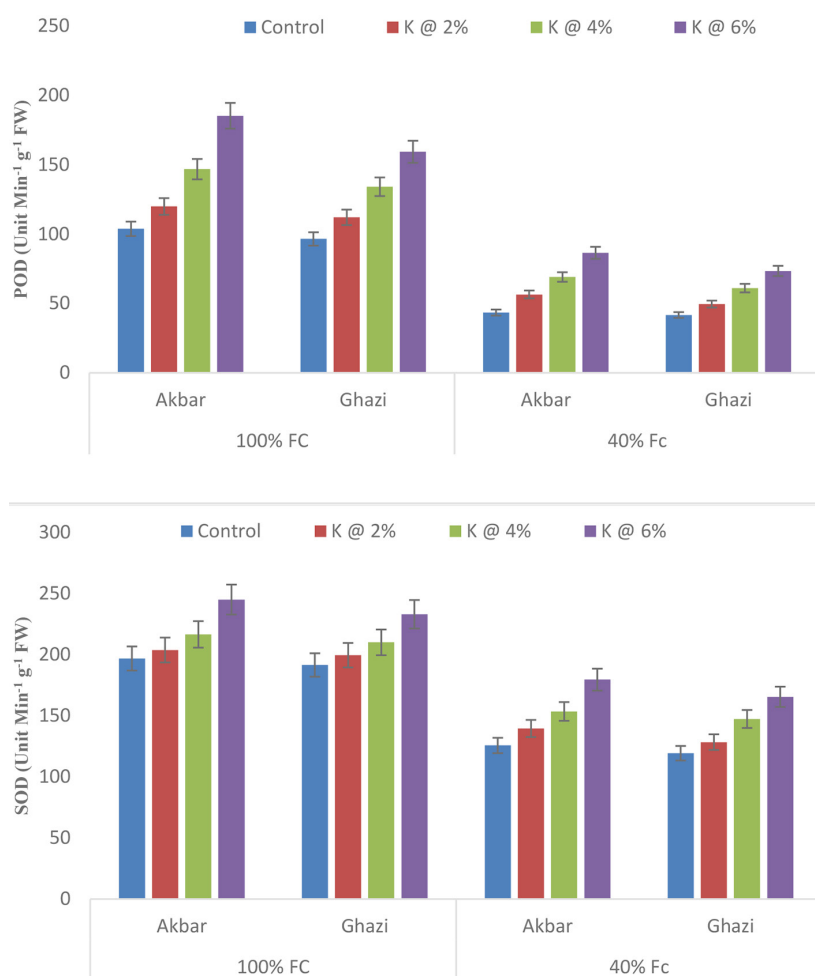


Figure 5. Foliar-applied potassium effects on peroxidase (POD) and superoxide dismutase (SOD) activity in wheat cultivars under normal and drought stress conditions (bars represent means $\pm$ standard deviation of three independent replicates)

APX activity, strengthening the ascorbate–glutathione cycle, and promoting scavenging of hydrogen peroxide under DS (Ahmad et al., 2018).

Along with APX and CAT, SOD and POD served as a primary defense line against the oxidative stress caused by prolonged water scarcity (El-Metwally et al., 2025). In our study, a 6% dose (26.94 g K per liter of water) of foliage-applied K increased POD and SOD activity, especially for the Akbar cultivar, indicating greater drought tolerance than other cultivars. The SOD efficiently catalyzed superoxide radicals (O_2^-) conversion into hydrogen peroxide (H_2O_2) and molecular oxygen, which significantly hampered oxidative stress (Munsif et al., 2022a). Likewise, K-mediated POD biosynthesis promoted H_2O_2 reduction with the help of phenolic compounds and complemented the activities of APX and CAT in the apoplast. In concurrence with our findings, it was inferred that K supplementation improved SOD activity

because K acted as a cofactor for SOD biosynthesis and assisted drought-stressed plants in preventing the denaturation of proteins. Moreover, exogenous application of K in different doses played a central role in maintaining ionic balance in the cytosol as well as the maintenance of pH, which improved the biosynthesis of POD during the periods of drought (Salman et al., 2025). Another study reported that foliage-applied K maintained turgor pressure and ionic balance under DS, along with ensuring the release of energy, which activated POD and SOD for preventing oxidative damage by scavenging superoxide radicals (El-Metwally et al., 2025). Overall, these findings suggest that a higher concentration of foliar-applied K holds potential to overcome the limitation of lower foliar absorption efficiency owing to cuticle thickening and reduced transpiration in wheat under DS, ensuring a robust physiological effectiveness in ameliorating the deleterious effects of water shortage.

CONCLUSIONS

The findings of this study were in concurrence with the postulated hypothesis, as the tested cultivars of wheat exhibited dose-dependent drought mitigation responses to foliar application of Overall, the Akbar cultivar outperformed Ghazi as far as growth traits (length, fresh and dry weights of root and shoot) and response to K supplementation (especially 6% concentration of K) were concerned, indicating Akbar possesses better tolerance and resilience to DS, indicating its suitability for cultivation in drought-prone environments. Additionally, it was also inferred that exogenous K application, particularly in 6% concentration (26.94 g K per liter of water), imparted resilience against drought in wheat, which may be attributed to a more vigorous root system (as indicated by greater length and weight of roots), that likely enabled wheat plants to extract more soil moisture under DS. Moreover, exogenous K application enhanced the biosynthesis of chlorophyll (*a*, *b*, and total) and carotenoids, suggesting that K played a protective role in sustainably maintaining the integrity as well as functions of the photosynthetic apparatus under induced DS. Moreover, K foliar application strengthened the antioxidant defense system by effectively upregulating the biosynthesis of APX, CAT, POD, and SOD, which probably initiated the detoxification process of H₂O₂ and prevented oxidative damage to cells, thereby contributing to plants' potential to withstand mild spells of drought. Collectively, these findings contribute to a better understanding of the physiological and biochemical mechanisms conferring resilience to DS and highlight the potential of the drought-ameliorative role of foliar-applied K in wheat. Future research needs to expand these results by testing a larger number of promising wheat cultivars for drought tolerance-based screening and optimizing K applied doses at varying growth stages of the crops under different drought intensities (20–70% of FC).

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