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Comparative Morphological Response of Wheat Genotypes (Triticum aestivum L.) to Potassium Treatments Under Irrigated and Terminal Drought Conditions

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Abstract: Worldwide wheat productivity faces limitations due to environmental stresses, of which drought is a key factor, necessitating effective nutrient management strategies such as potassium (K) application to enhance stress tolerance and yield stability. Field experiments were conducted during the 2022-23 growing season to analyze the response of different genotypes to K concentrations under terminal drought conditions (TDC). Field experiments conducted during the 2022-23 growing season analyzed the response of eight wheat genotypes to three potassium concentrations (K1: 0%, K2: 1%, K3: 2%) under TDC. The study showed a significant positive correlation between yield and several plant parameters, including height, panicle length, number of spikelets, flag leaf area, yield per plant and thousand-grain weight. Results showed that K3 application resulted in significant improvements, especially under stressful conditions. Under irrigation, the plant height of Ghazi-2019 increased by 15% (99 cm), while the thousand-kernel weight of Subhani-2021 increased by 20% (69 g). In TDC, Akbar-19 yields increased by 25% (7.7 g/plant) using K3 compared to K1. Faisalabad-2008 yield increased by 30% under K2 (7.1 g/plant) irrigation. Applying K to wheat under both irrigation and TDS can significantly increase wheat yield in the later stages of growth.

Keywords: Wheat, Drought, Potassium, Grain yield, Genotypes

INTRODUCTION

The productivity of wheat is increasingly affected by environmental stress. Drought is a key limiting factor that changes physiological and biochemical processes, reduces yields, and threatens global food security (Choudhary *et al.*, 2021). Due to the combined effects of drought and desertification, approximately 120 million hectares of agricultural land have disappeared globally, averaging 12 million hectares per year in the past ten years (2014-2024). While causing significant losses in productivity droughts disproportionately affect agricultural regions in South America, Africa, Europe and South Asia (Marques, 2020).

Drought affects 20-25% of the global wheat area, with yield reductions ranging from 10% to 76% depending on the severity of the drought and the crop growth stage in terms of wheat production (Clarke *et al.*, 2021; Lan *et al.*, 2022). In the United States, nearly 48% of winter wheat-producing areas were affected by drought in 2023, while in Canada, wheat production fell by 38.5% in 2021 due to drought (Coughlan de Perez *et al.*, 2023; Khalili *et al.*, 2024). Over the past 50 years (1974-2024), Pakistan has experienced several severe droughts that have had a profound impact on its agricultural sector. During the worst drought period, especially between 2000 and 2002, the country suffered approximately 60% of total area (Adnan & Ullah, 2020). Wheat production is particularly vulnerable, with droughts reducing

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yields by up to 50% in the worst years, such as 2000-2002, 2015 and 2018 (Saleem *et al*., 2022). Looking ahead, projections indicate that ongoing climate change and persistent droughts could lead to a decline in wheat production of up to 50% in South Asia, including Pakistan, by 2050, posing a significant threat to food security in the region (Pequeno *et al*., 2021).

Wheat (*Triticum aestivum* L) is an important staple food with a hexaploid genome (2n = 6x = 42), possesses a diverse genetic composition across its chromosomes (Gupta & Vasistha, 2018). Throughout history, wheat contains 21% nutrition of the world's population, supplying approximately 19% of global calories and 21% of protein (Davies & Jakeman, 2020). A global wheat production of 786 million tons was reported in 2023 by the Food and Agriculture Organization (Dadrasi *et al*., 2023). Despite a small decline in the planted area, the projected wheat production for the 2023/2024 season is expected to reach 27.0 million tons, indicating a two percent increase compared to the previous year. The productivity of wheat faces significant threats from abiotic stresses, particularly heat and drought, posing a considerable risk to global food security (Davies & Jakeman, 2020; Dohlman *et al*., 2022).

Water serves as an indispensable lifeline for wheat, nurturing its growth from germination to maturity and ensuring its survival as a vital staple crop worldwide. Understanding the optimal water requirements at different stages of wheat's growth cycle is vital for maximizing crop yields and ensuring successful cultivation practices. Water requirements of wheat crops in Pakistan vary depending on soil texture. In sandy soils, less water is needed for frequent irrigation each growing season. Due to its balance of water retention and drainage, fertile soil requires moderate irrigation, about 400-450 mm per season. Clay soils have high water retention and require less frequent but larger amounts of irrigation, about 350-400 mm per season (Chaudhari *et al*., 2024). It is recommended to maintain soil moisture at at least 50% of crop evapotranspiration to ensure healthy crop growth. To achieve optimal growth and maximize yield, the availability of water at all stages of wheat's growth, beginning from germination and persisting throughout the various growth phases, is of utmost importance (Himanshu *et al*., 2021; Slafer *et al*., 2021).

Various techniques have been employed to help plants deal with drought stress. However, in modern agricultural research, particular attention is being given to the exogenous application of compatible solutes such as amino acids, proline, and potassium (K), among others. K serves as an important stress-alleviating plant nutrient that mitigates the adverse effects of abiotic stresses through the regulation of biological and molecular processes in plants (Basit *et al*., 2023). The utilization of Optimal K reduces ROS production, enhances antioxidant activity, and alleviates oxidative stress in drought-stressed sesame plants. Numerous studies have investigated the relationship between water stress, K nutrition, and field crops, wheat among them (Fang *et al*., 2022).

The role of K in mitigating the effects of drought in wheat has been the focus of research since the mid-20th century. Pioneering work by Dr. A. Wallace and his team in the 1960s showed that K applications can enhance water uptake and retention, thereby improving drought tolerance in crops, including wheat (Baranski, 2022). Subsequent studies have delved into the physiological and biochemical mechanisms underlying potassium's drought resistance. Early studies confirmed the importance of K in processes such as enzyme activation, osmoregulation and stomatal regulation, which are critical for maintaining plant health under stressful conditions. By the second half of the 20th century, the systematic use of K to reduce drought stress in wheat became more common (Mostofa *et al*., 2022). However, there is a dearth of extensive research focused on the interactive response of wheat genotypes to the application of K under water stress conditions, specifically in arid environments, concerning susceptibility to drought and yield-related traits. Thus, research objective was to assess the impact of K application on a range of wheat genotypes under irrigated and terminal drought conditions (TDC).

MATERIALS and METHODS

A field experiment was conducted in a semi-arid region at the University of Layyah (30.849° N, 71.094° E) during the 2022-23 growing season to analyze the response of various wheat genotypes under irrigated and water deficit conditions. To carry out this research, a total of eight commonly cultivated wheat varieties viz. Champion 2023, Faislabad 2008, Ghazi 2019, Fakhare Bhakhar, Dilkash 2021, Subhani 2021, Bhakhar Star-2019, and Akbar-2019 in Pakistan were chosen for cultivation. The experiment was conducted using a randomized complete block design (RCBD) with three replications.. Soil analysis was conducted prior to the trial, revealing a pH of 8.19, electrical conductivity (EC) of 1.95 dS m^{-1}, and extractable phosphorus (P) and K concentrations of 23 mg kg^{-1} and 62 mg kg^{-1}, respectively, based on standards from the Soil Fertility and Research Institute Punjab, Lahore (Qazi, 2021). Nitrogen (N) and phosphorus (P) applications were calculated based on the recommended ratio of 50:25 kg $acre^{-1}$ (Jagdish, 2022). Optimal irrigation was applied during the flowering and grain-filling stages under non-stress conditions.. Drought stress was induced during the grain-filling stage by withholding irrigation as part of the experimental protocol. After 90 days of sowing, different levels of foliar K were applied to the genotypes to assess their responses under the experimental conditions. The recommended potassium application rate is 12 kg $acre^{-1}$. Three levels of potassium were applied: 0% (K1, no K application), 1% (K2, recommended rate), and 2% (K3, double the recommended rate).. Eight commonly cultivated wheat varieties were selected for this study: Champion 2023, Faisalabad 2008, Ghazi 2019, Fakhare Bhakhar, Dilkash 2021, Subhani 2021, Bhakhar Star 2019, and Akbar 2019. The collected data were analyzed using ANOVA with statistical software to identify significant differences between treatment groups.

RESULTS and DISCUSSION

Data on various morphological parameters were collected at the maturity stage of wheat. Traits like plant height, peduncle length, spike length, flag leaf area, and number of tillers showed highly significant individual effects for drought, genotypes, and K treatments. Plant height, flag leaf area, 1000-grain weight, and yield per plant exhibited highly significant interactive effects of all three treatments (Table 1). The maximum plant height of 104 cm was observed in Ghazi 2019 under TDC with K2 treatment, while the minimum height was 83.6 cm in Champion 2023 under irrigated conditions with K2. Under irrigated conditions, Subhani 2021 exhibited the highest peduncle length of 43 cm with K1 treatment, while Akbar-19 recorded the longest peduncle length of 43.6 cm under TDC with K3. Spike lengths varied, with Dilkash 2021 achieving the maximum of 13.3 cm under drought and K3. The highest number of spikelets per spike was recorded in Dilkash 2021 under all conditions, with 17.67 spikelets. Flag leaf area also varied significantly, with Akbar-19 showing the largest area of 26.33 cm^2 under irrigated conditions and K3, while Akbar-19 recorded the highest area of 26.33 cm^2 under drought and K3.

Under irrigated conditions, the maximum 1000-grain weight was observed in Champion 2023 with 46.6 g under K1 treatment, while the minimum was 32.3 g in Ghazi 2019 under K2 treatment. Under TDC, the maximum 1000-grain weight was recorded in Ghazi 2019 with 43.6 g under K3, while the minimum was 32.6 g in Dilkash 2021 under K2 treatment. Champion 2023 achieved the highest yield of 45.3 g/plant under K1, and the lowest yield of 29.6 g/plant was observed in Subhani 2021 under K3 in irrigated conditions. TDC, Ghazi 2019 recorded the highest yield of 43.3 g/plant under K2, while the lowest yield of 30.6 g/plant was observed in Bhakhar Star-19 under K1.

Table 1. *Analysis of variance of various traits showing the interaction between genotypes, drought and potassium.*

	Plant Height	Peduncle Length	Spike Length	Number of Spikelets	Flag Leaf Area	Number of Tillers	1000 Grain Weight	Yield per Plant
Drought	540.56**	100.00**	13.4**	18.06*	286.2**	1207**	98.34 ns	1.01ns
Genotypes	67.64**	218.64**	4.67**	21.41**	75.75**	934**	64.59 ns	3.57**
Potassium	121.18**	10.09ns	6.88**	5.77ns	437.6**	418**	1320.8**	19.59**
Drought x Genotypes	107.62**	13.85ns	6.34**	16.14**	60.96**	1728**	324.34**	8.15**
Drought x Potassium	23.77ns	66.14**	2.17ns	6.58 ns	19.38*	961**	389.78**	2.88**
Genotypes x Potassium	41.10**	13.09ns	2.05*	2.78 ns	34.36**	328**	94.76*	1.38**
Drought x Genotypes x Potassium	31.38**	18.38*	1.36ns	2.68 ns	24.41**	781**	177.28**	1.91**

*: Significant; **: highly significant; ns: Non-significant

Under irrigated conditions, Champion 2023 showed plant heights of 86.6 cm (K1), 83.6 cm (K2), and 85 cm (K3). Faisalabad 2008 reported plant heights of 85.6 cm (K1), 87 cm (K2), and 82 cm (K3). Ghazi 2019 exhibited plant heights of 84 cm (K1), 92 cm (K2), and 99 cm (K3). Fakhare Bhakhar showed plant heights of 84 cm (K1), 91.6 cm (K2), and 87 cm (K3). Dilkash 2021 showed plant heights ranging from 90 cm to 92 cm across K1, K2, and K3 applications. Subhani 2021 had plant heights of 85 cm (K1), 92 cm (K2), and 90.6 cm (K3). Bhakhar Star-19 showed plant heights of 86.6 cm (K1), 92.3 cm (K2), and 94 cm (K3). Akbar-19 exhibited plant heights of 89 cm (K1), 88 cm (K2), and 95.6 cm (K3) (Fig 1-a).

Under TDC, Champion 2023 showed plant heights of 96.6 cm (K1), 90.3 cm (K2), and 95 cm (K3). Faisalabad 2008 exhibited heights of 94.6 cm (K1), 94.6 cm (K2), and 91.3 cm (K3). Ghazi 2019 demonstrated heights of 93.3 cm (K1), 104 cm (K2), and 93 cm (K3). Fakhare Bhakhar showed plant heights of 96.3 cm (K1), 96 cm (K2), and 95 cm (K3). Dilkash 2021 had plant heights of 90.3 cm (K1), 94.3 cm (K2), and 99 cm (K3). Subhani 2021 reported heights of 87.6 cm (K1), 92 cm (K2), and 95.6 cm (K3). Bhakhar Star-19 resulted in plant heights of 88.6 cm (K1), 91.6 cm (K2), and 90.6 cm (K3) (Fig 1-b).

Under irrigated conditions, Champion 2023 showed peduncle lengths 30 cm (K1), 32.6 cm (K2), and 32.3 cm (K3); Faisalabad 2008 recorded 37.3 cm (K1), 32.6 cm (K2), and 39 cm (K3); Ghazi 2019 had 38 cm (K1), 39 cm (K2), and 40.3 cm (K3); Fakhare Bhakhar resulted 37 cm (K1), 35 cm (K2), and 29 cm (K3); Dilkash 2021 showed 30.6 cm (K1), 31.6 cm (K2), and 31 cm (K3); Subhani 2021 had 43 cm (K1), 40.3 cm (K2), and 39.6 cm (K3); Bhakhar Star-19 showed 38 cm (K1), 37.6 cm (K2), and 36.3 cm (K3); and Akbar 19 showed 42 cm (K1), 37.6 cm (K2), and 35 cm (K3) (Fig. 1-c).

Under TDC Champion 2023 recorded peduncle lengths of 43 cm (K1), 35.3 cm (K2), and 33.3 cm (K3); Faisalabad 2008 had 37.3 cm (K1), 37.6 cm (K2), and 41 cm (K3); Ghazi 2019 exhibited 43 cm (K1), 44 cm (K2), and 40 cm (K3); Fakhare Bhakhar showed 34 cm (K1), 36.3 cm (K2), and 35.6 cm (K3); Dilkash 2021 had 31.6 cm (K1), 32.3 cm (K2), and 32.3 cm (K3); Subhani 2021 recorded 33.3 cm (K1), 43 cm (K2), and 41 cm (K3); Bhakhar Star-19 exhibited 34.3 cm (K1), 40.6 cm (K2), and 40 cm (K3); and Akbar-19 showed 40 cm (K1), 42.3 cm (K2), and 43.6 cm (K3) (Fig. 1-d).

Under irrigated conditions, Champion 2023 showed spike lengths of 10.3 cm (K1), 10.6 cm (K2), and 9 cm (K3). Faisalabad 2008 showed spike lengths of 11.3 cm (K1), 12.3 cm (K2), and 10.6 cm (K3). Ghazi 2019 had spike lengths of 10.3 cm (K1), 10.3 cm (K2), and 10.6 cm (K3). Fakhare Bhakhar recorded spike lengths of 9.6 cm (K1), 11.6 cm (K2), and 11 cm (K3). Dilkash 2021 demonstrated spike lengths of 12 cm (K1), 12.3 cm (K2), and 13.3 cm (K3). Subhani 2021 had spike lengths of 11.3 cm (K1), 12.6 cm (K2), and 11.6 cm (K3). Bhakhar Star-19 showed spike lengths of 12 cm (K1), 12 cm (K2), and 11.6 cm (K3). Akbar-19 showed 10 cm (K1), 11.3 cm (K2), and 10.6 cm (K3) (Fig. 1-e).

Under TDC, Champion 2023 resulted spike lengths of 10.33 cm (K1), 10.67 cm (K2), and 10.67 cm (K3). Faisalabad 2008 had spike lengths of 9 cm (K1), 10 cm (K2), and 9.67 cm (K3). Ghazi 2019 recorded spike lengths of 12 cm (K1), 12.67 cm (K2), and 10.33 cm (K3). Fakhare Bhakhar showed spike lengths of 11 cm (K1), 10.67 cm (K2), and 11 cm (K3). Dilkash 2021 exhibited spike lengths of 10 cm (K1), 11 cm (K2), and 13 cm (K3). Subhani 2021 had spike lengths of 9.33 cm (K1), 10.67 cm (K2), and 10.33 cm (K3). Bhakhar Star-19 demonstrated consistent spike lengths of 10 cm (K1 and K2) and 10.67 cm (K3). Akbar-19 recorded spike lengths of 9 cm (K1), 10.33 cm (K2), and 12 cm (K3) (Fig. 1-f).

Under irrigated conditions, the number of spikelets per spike varied among wheat varieties. Champion 2023 recorded 16.67 spikelets under K1, 16.33 spikelets under K2, and 15.33 spikelets under K3. Faisalabad 2008 showed 13.67 spikelets under K1, 14.33 spikelets under K2, and 14.67 spikelets under K3. For Ghazi 2019, the spikelet counts were 12.67 under K1, 12.33 under K2, and 13 under K3. Fakhare Bhakhar showed spikelet counts of 11.67 under K1, 14.67 under K2, and 13 under K3. Dilkash 2021 demonstrated the highest spikelet count, consistently recording 17.67 spikelets under K1 and K3, 17.33 spikelets under K2 conditions.). Subhani 2021 recorded 15.67 spikelets under K1 and 15.33 spikelets under both K2 and K3 conditions. Bhakhar Star-19 showed consistent spikelet counts of 14.33 under K1 and K2 conditions, 15.33 under K3. Akbar-19 recorded 15 spikelets under K1, 16 spikelets under K2, and 14.67 spikelets under K3 (Fig. 1-g).

Under TDC Champion 2023 showed the number of spikelets per spike of 15.67 spikelets (K1), 14.00 spikelets (K2), and 15.00 spikelets (K3). Faisalabad 2008 exhibited slightly lower the number of spikelets per spike of 13.33 spikelets (K1), 12.33 spikelets (K2), and 13.33 spikelets (K3). Ghazi 2019 demonstrated the number of spikelets per spike of 16.33 spikelets (K1), 16.67 spikelets (K2), and 15.00 spikelets (K3). Fakhare Bhakhar demonstrated the number of spikelets per spike of 12.67 spikelets (K1), 14.00 spikelets (K2), and 16.00 spikelets (K3). Dilkash 2021 had the number of spikelets per spike of 14.33 spikelets (K1), 15.33 spikelets (K2), and 18.33 spikelets (K3). Subhani 2021 presented a broader range of the number of spikelets per spike, measuring 12.33 spikelets (K1), 14.00 spikelets (K2), and the highest value of 13.33 spikelets (K3). Bhakhar Star-19 showed consistent spikelet counts of 12.33 under K1, 11.00 under K2, 13.67 under K3. Akbar-19 recorded 12.67 spikelets under K1, 13.00 spikelets under K2, and 15.33 spikelets under K3 (Fig. 1-h).

Under irrigated conditions, the flag leaf area (cm^2) exhibited significant variation across different wheat varieties. Champion 2023 recorded flag leaf areas of 12.33 cm^2 (K1), 15.00 cm^2 (K2), and 16.67 cm^2 (K3). In Faisalabad 2008, the values were slightly lower, with 11.33 cm^2 for K1, 21.00 cm^2 for K2, and 17.67 cm^2 for K3. Ghazi 2019 demonstrated a broader range with flag leaf areas of 16.67 cm^2 (K1), 21.67 cm^2 (K2), and the highest recorded value of 25.33 cm^2 for K3. For Fakhare Bhakhar, the areas were 15.67 cm^2 (K1), 16.00 cm^2 (K2), and 18.00 cm^2 (K3). Dilkash 2021 exhibited higher values with 21.33 cm^2 (K1), 17.33 cm^2 (K2), and 24.00 cm^2 (K3). Subhani 2021 showed flag leaf areas of 13.00 cm^2 (K1), 14.67 cm^2 (K2), and 20.00 cm^2 (K3). Bhakhar Star-19 recorded lower values of 10.00 cm^2 (K1), 15.00 cm² (K2), and 21.67 cm² (K3). Akbar-19 showed flag leaf areas of 16.00 cm² (K1), 18.00 cm² (K2), and 26.33 cm² (K3). (Fig. 1-i).

Under TDC, Champion 2023 recorded flag leaf areas of 20.33 cm² (K1), 24.33 cm² (K2), and 19.00 cm² (K3). For Faisalabad 2008, the areas were measured at 15.67 cm² for K1, 12.67 cm² for K2, and 18.33 cm² for K3. Ghazi 2019 exhibited a broader range, with 18.67 cm² (K1), 25.00 cm² (K2), and 25.67 cm² (K3). The variety Fakhare Bhakhar recorded flag leaf areas of 16.00 cm² (K1), 25.00 cm² (K2), and 23.00 cm² (K3). Dilkash 2021 showed values of 17.00 cm² (K1), 18.00 cm² (K2), and 22.33 cm² (K3). In Subhani 2021, the flag leaf areas were 15.33 cm² for K1, 22.33 cm² for K2, and 15.67 cm² for K3. Bhakhar Star-19 demonstrated significant results, with 18.00 cm² (K1), 26.33 cm² (K2), and the highest value of 29.00 cm² (K3) Akbar-19 showed flag leaf areas of 18.00 cm² (K1), 17.67 cm² (K2), and 29.00 cm² (K3) (Fig. 1-j).

Under irrigated conditions, Champion 2023, the tiller numbers recorded were 57.67 (K1), 71.67 (K2), and 56.67 (K3). Faisalabad 2008 exhibited tiller counts of 73.67 (K1), 68.33 (K2), and 50.33 (K3). The variety Ghazi 2019 showed tiller numbers of 65.00 (K1), 87.67 (K2), and 70.67 (K3). Fakhare Bhakhar resulted a tiller count of 83.33 (K1), 60.33 (K2), and 71.67 (K3). In the case of Dilkash 2021, the numbers were 75.00 (K1), 91.33 (K2), and 72.33 (K3). Subhani 2021 had tiller counts of 83.67 (K1), 79.00 (K2), and 87.33 (K3). Bhakhar Star-19 showed a tiller production of 77.00 (K1), 97.33 (K2), and 89.00 (K3). Akbar-19 showed tiller numbers of 63.67 (K1), 84.00 (K2), and 99.00 (K3). (Fig. 1-k).

Under TDC, in Champion 2023, the number of tillers recorded were 130.67 (K1), 117.33 (K2), and 113.67 (K3). Faisalabad 2008 exhibited tiller counts of 123.00 (K1), 125.67 (K2), and 190.00 (K3). The variety Ghazi 2019 showed tiller numbers of 144.67 (K1), 145.67 (K2), and 129.33 (K3). Fakhare Bhakhar resulted a tiller count of 156.67 (K1), 158.67 (K2), and 164.00 (K3). In the case of Dilkash 2021, the numbers were 122.00 (K1), 120.00 (K2), and 153.00 (K3). Subhani 2021 had tiller counts of 118.33 (K1), 115.00 (K2), and 126.67 (K3). Bhakhar Star-19 showed a tiller production of 134.33 (K1), 128.33 (K2), and 132.67 (K3). Finally, Akbar-19 exhibited tiller numbers of 121.67 (K1), 116.67 (K2), and 117.67 (K3) (Fig. 1-l).

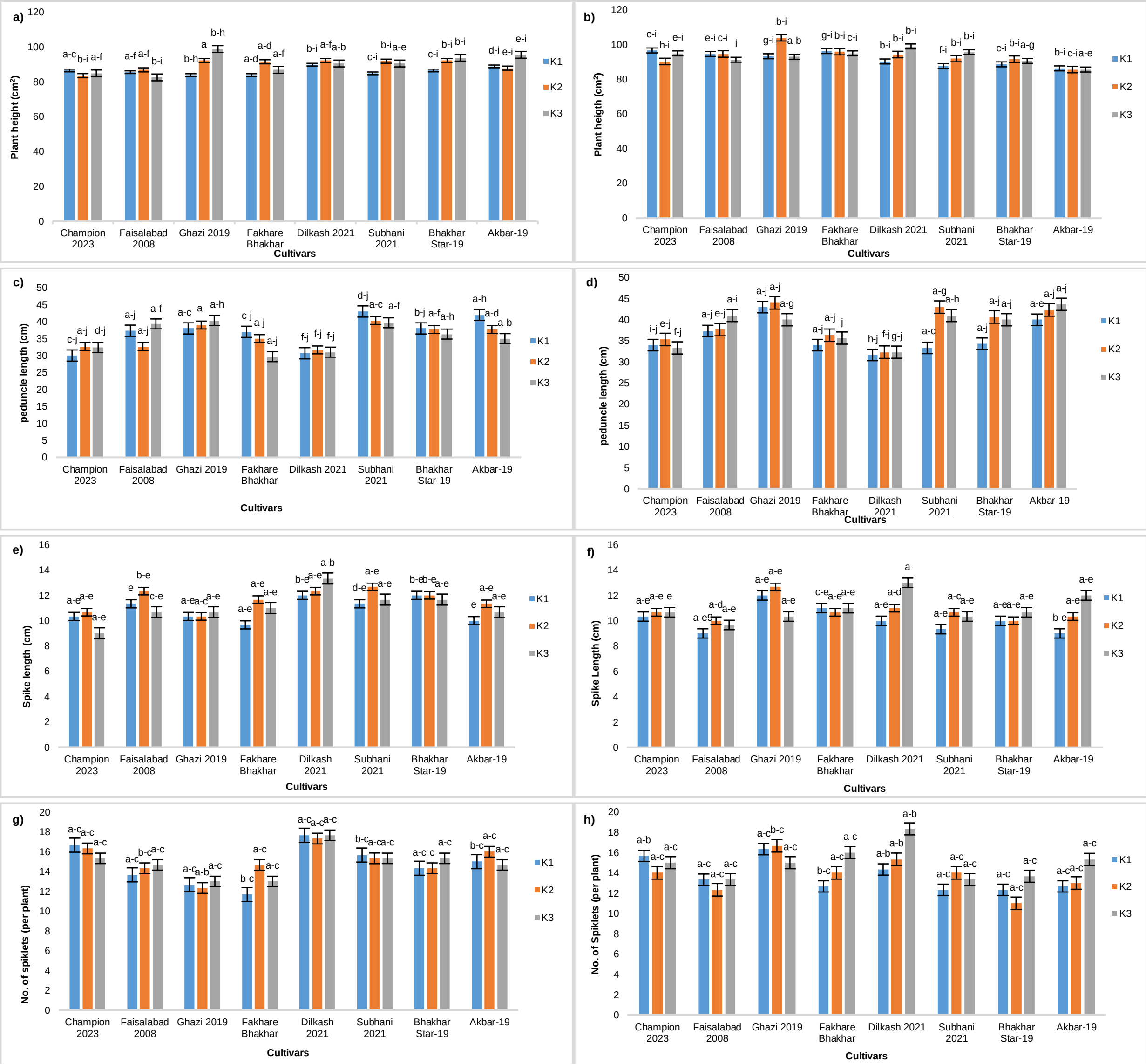
Under irrigated conditions, Champion 2023 showed 1000 grain weights of 41.67 g (K1), 50.00 g (K2), and 54.00 g (K3). In Faisalabad 2008, the weights recorded were 53.00 g (K1), 52.00 g (K2), and 57.00 g (K3). The Ghazi 2019 study showed weights of 40.67 g (K1), 46.33 g (K2), and 58.33 g (K3). Fakhare Bhakhar resulted weights of 28.33 g (K1), 41.33 g (K2), and 56.33 g (K3). In Dilkash 2021, the weights were 41.33 g (K1), 56.67 g (K2), and 62.67 g (K3). Subhani 2021 recorded weights of 40.00 g (K1), 44.33 g (K2), and 69.00 g (K3). Bhakhar Star-19 showed weights of 46.00 g (K1), 44.67 g (K2), and 56.67 g (K3). Finally, Akbar-19 exhibited weights of 48.67 g (K1), 28.67 g (K2), and 47.67 g (K3). The maximum 1000 grain weight under irrigated conditions was observed in Subhani 2021 (K3) with 69.00 g, while the minimum was recorded in Fakhare Bhakhar (K1) with 28.33 g. (Fig. 1-m).

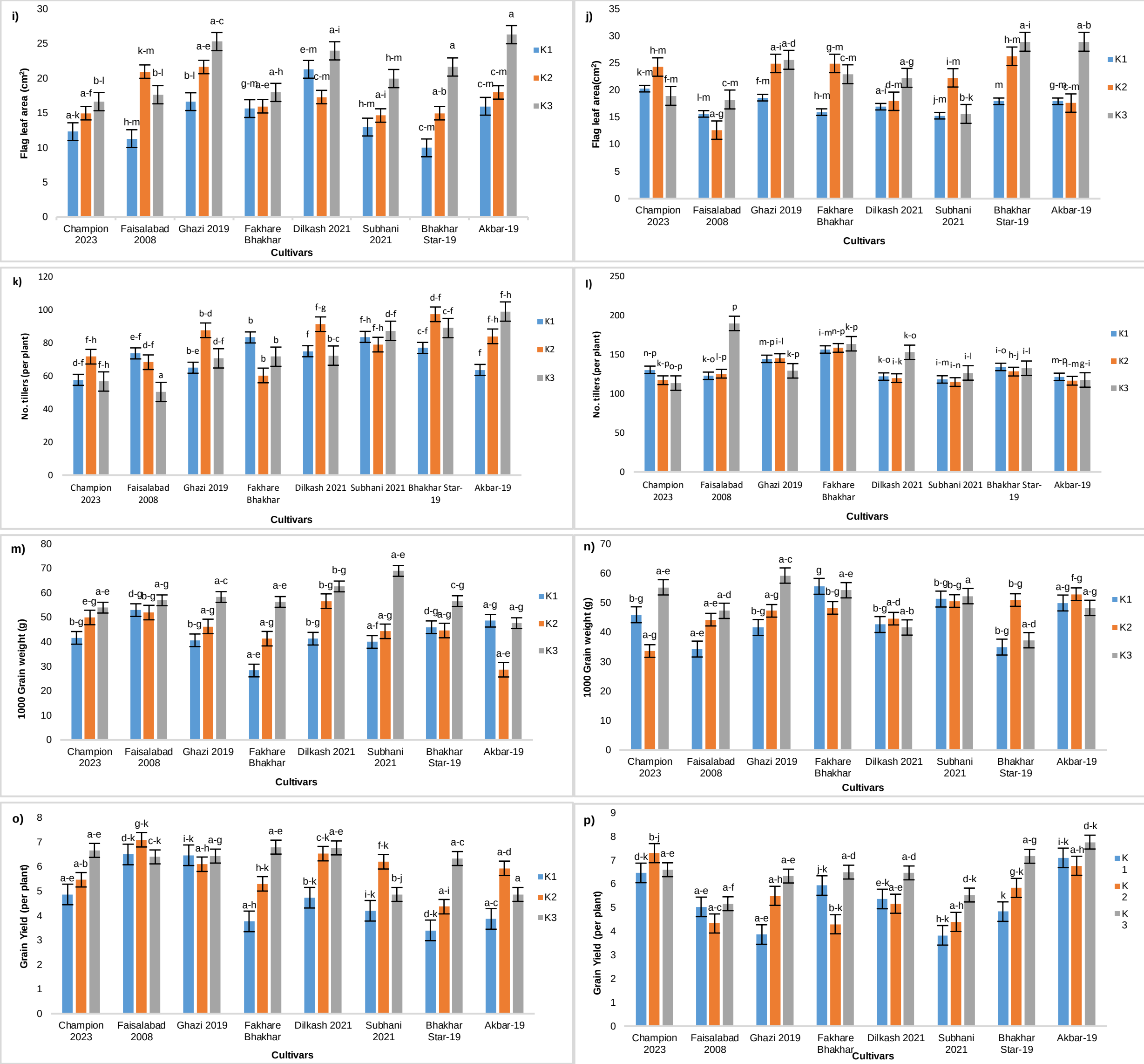
Under TDC, in Champion 2023, the 1000 grain weights were recorded as 46.00 g (K1), 33.67 g (K2), and 55.33 g (K3). The Faisalabad 2008 study exhibited weights of 34.33 g (K1), 44.33 g (K2), and 47.33 g (K3). The Ghazi 2019 results showed weights of 41.67 g (K1), 47.33 g (K2), and 59.33 g (K3). For Fakhare Bhakhar, the recorded weights were 55.67 g (K1), 48.33 g (K2), and 54.33 g (K3). In Dilkash 2021, the weights were 42.67 g (K1), 44.67 g (K2), and 41.67 g (K3). Subhani 2021 showed weights of 51.33 g (K1), 50.67 g (K2), and 52.33 g (K3). The Bhakhar Star-19 study recorded weights of 35.00 g (K1), 51.00 g (K2), and 37.33 g (K3). Finally, Akbar-19 exhibited weights of 50.00 g (K1), 53.00 g (K2), and 48.33 g (K3). The maximum 1000 grains weight under TDC was observed in Ghazi

2019 (K3) with 59.33 g, while the minimum was recorded in Champion 2023 (K2) with 33.67 g (Fig. 1-n).

The maximum average grain yield per plant under irrigated conditions was achieved by Faisalabad 2008 (K2) with 7.1, while the minimum was recorded in Bhakhar Star-19 (K1) with 3.4. In Champion 2023, the average grain yields per plant were 4.87 (K1), 5.47 (K2), and 6.67 (K3). The Faisalabad 2008 study recorded yields of 6.50 (K1), 7.10 (K2), and 6.40 (K3). Ghazi 2019 showed yields of 6.47 (K1), 6.10 (K2), and 6.43 (K3). Fakhare Bhakhar reported yields of 3.77 (K1), 5.30 (K2), and 6.80 (K3). In Dilkash 2021, the yields were 4.73 (K1), 6.53 (K2), and 6.77 (K3). Subhani 2021 had yields of 4.20 (K1), 6.20 (K2), and 4.87 (K3). Bhakhar Star-19 recorded yields of 3.40(K1), 4.37 (K2), and 6.33 (K3). Finally, Akbar-19 exhibited yields of 3.87 (K1), 5.93 (K2), and 4.87 (K3) (Fig. 1-o).

The maximum average grain yield per plant under TDC was observed in Akbar-19 (K3) with 7.77, while the minimum was recorded in Subhani 2021 (K1) with 3.83. In Champion 2023, the average grain yields per plant were 6.47 (K1), 7.30 (K2), and 6.60 (K3). Faisalabad 2008 recorded yields of 5.03 (K1), 4.33 (K2), and 5.17 (K3). The Ghazi 2019 study showed yields of 3.87 (K1), 5.50 (K2), and 6.33 (K3). Fakhare Bhakhar exhibited yields of 5.93 (K1), 4.30 (K2), and 6.50 (K3). In Dilkash 2021, the yields were 5.37 (K1), 5.17 (K2), and 6.47 (K3). Subhani 2021 had yields of 3.83 (K1), 4.40 (K2), and 5.53 (K3). Bhakhar Star-19 reported yields of 4.83 (K1), 5.83 (K2), and 7.17 (K3). Finally, Akbar-19 achieved yields of 7.10 (K1), 6.77 (K2), and 7.77 (K3). (Fig. 1-p).





(K1: 0% potassium spray; K2: 1% Potassium foliar spray; K3: 2% Potassium foliar spray.)

Figure 1. a) Effect of K on plant height in irrigated conditions. **b)** Effect of K on plant height under drought conditions. **c)** Effect of K on peduncle length under irrigated conditions. **d)** Effect of K on peduncle length under drought conditions. **e)** Effect of K on spike length under irrigated conditions. **f)** Effect of K on spike length under drought conditions. **g)** Effect of K on spikelets per spike under irrigated condition. **h)** Effect of K on spikelets per spike under drought condition. **i)** Effect of K on flag leaf area under irrigated conditions. **j)** Effect of K on flag leaf area under drought conditions. **k)** Effect of K on number of tillers under irrigated conditions. **l)** Effect of K on number of tillers under drought conditions. **m)** Effect of K on thousand grain weight under irrigated conditions. **n)** Effect of K on thousand grain weight under drought conditions. **o)** Effect of K on grain yield under irrigated conditions. **p)** Effect of K on grain yield under drought conditions.

Correlation

Correlation is a basic term often to determine whether two morphological or physiological parameters positively or negatively affect each other. Correlation analysis can be used to evaluate the significance level of two traits (Pour-Aboughadareh *et al*., 2020). Plant height demonstrates a highly significant association with the number of tillers, while spike length exhibits a strong correlation with itself. Additionally, flag leaf area shows a highly significant correlation with plant height, yield per plant, and 1000-grain weight (Table 2). In irrigated conditions, characteristics including flag leaf area, plant height, peduncle length, shoot length, and 1000-grain weight have favorable correlations with yield, according to correlation analysis. Plant height, flag leaf area, peduncle length, shoot length, and 1000-grain weight all show stronger direct effects on yield, indicating that these traits will increase production. There was a substantial positive association found between flag leaf area and peduncle length, spike length, spikelets per plant, and yield per plant during TDC (Table 3). Plant height, spike length, and the number of tillers all exhibit positive and substantial correlations. Spike length also exhibits a positive and highly significant association with the number of spikelets per plant. However, plant height and spike length have a negative correlation with yield per plant and 1000 grains weight, respectively.

Table 2. *Correlation table showing the effects of traits on yield of wheat in irrigatedconditions*

	Plant-height	Peduncle-length	Spike-length	Number of spikelet	Flag leaf area	Number of tillers	1000 grains weight	Yield per plant
Plant-height	1							
Peduncle-length	-0.0627	1						
Spike-length	0.3253*	0.0708	1					
Number of spikelet	0.3848	0.0004**	0.6343**	1				
Flag leaf area	0.0354	0.3274**	0.2726	0.2731	1			
Number of tillers	0.3226**	0.0141*	0.1845	0.1418	0.0526	1		
1000 grains weight	0.0305	0.0992	-0.0098	-0.1283	0.0183**	0.0763	1	
Yield per plant	-0.1509	0.0585	0.1483	0.1295	0.3636**	-0.1232	0.0902	1

Table 3. *Correlation table showing the effects of traits on yield of wheat in drought conditions*

	Plant-height	Peduncle-length	Spike-length	Number of spikelets	Flag leaf area	Number of tillers	1000 grains weight	Yield per plant
Plant-height	1							
Peduncle-length	0.0582	1						
Spike-length	0.2979*	-0.0600	1					
Number of spikelet	0.0406	-0.2594*	0.3312**	1				
Flag leaf area	0.4618**	-0.1292	0.0833	-0.0416	1			
Number of tillers	0.3340**	0.1845	0.1707	0.0214	0.2055	1		
1000 grains weight	0.1569	-0.1386	0.1728	0.0133	0.3475**	-0.0426	1	
Yield per plant	0.0540	-0.2602*	0.0769	0.0073	0.352**	0.1754	0.349**	1

Path analysis

Path analysis was utilized to investigate the interrelationships between various traits or parameters and their correlation with yield, specifically grain yield. This analytical approach involved conducting correlation and regression analyses to discern both the direct and indirect effects of different traits on the yield. Results showed that under irrigated conditions there are high direct effects of 1000 grains weight and Flag leaf area on final yield while plant height, peduncle length and no. of tillers have negative direct effect with final yield i.e. grain yield (Table 4). Number of spikelets and spike length are positively correlated with the yield. Other indirect effects are 1000 grains weight through the number of tillers and plant height through the number of tillers and flag leaf areas on the yield. Under TDC flag leaf area and 1000 grain weight have high positive direct effect on grain yield while plant height, peduncle length and spikelets per plant have negative direct effect on yield (Table 5). Flag leaf area positively affects yield through 1000 grain yield.

Table 4. *Path analysis showing direct and indirect effects under irrigated conditions*

	Plant height	Peduncle length	Spike length	Number of spikelet	Flag leaf area	Number of tillers	1000 grains weight
Plant height	-0.1968	0.009773	0.02447	-0.01524	0.01173	-0.0621	0.005963
Peduncle length	0.004841	-0.08692	0.005326	-1.05	0.108636	-0.0027	0.019385
Spike length	-0.02513	-0.01104	0.092648	-0.02513	0.090443	-0.0355	-0.00191
Number of spikelets	-0.02973	-4.105	0.047714	0.080823	0.09063	-0.0273	-0.02508
Flag leaf area	-0.00273	-0.05106	0.020502	-0.01082	0.355555	-0.0101	0.003593
Number of tillers	-0.02492	-0.0022	0.013876	-0.00562	0.017444	-0.1147	0.014913
1000 grains weight	-0.00236	-0.01547	-0.00073	0.005083	0.006101	-0.0147	0.118273

Table 5. *Path analysis showing direct and indirect effects under drought conditions*

	Plant height	Peduncle length	Spike length	Number of spikelet	Flag leaf area	Number of tillers	1000 grains weight
Plant height	-0.0772	-0.00908	0.022408	-0.00161	0.153231	-0.06435	0.03067
Peduncle length	-0.0045	-0.15596	-0.00451	0.010277	-0.04289	-0.03555	-0.02709
Spike length	-0.0230	0.009359	0.07522	-0.01312	0.027644	-0.03289	0.033781
Number of spikelets	-0.0031	0.04046	0.024915	-0.03961	-0.0138	-0.00413	0.002598
Flag leaf area	-0.0356	0.020156	0.006267	0.001648	0.331828	-0.03959	0.06792
Number of tillers	-0.0258	-0.02878	0.012843	-0.00085	0.068181	-0.19266	-0.00833
1000 grains weight	-0.0121	0.021621	0.013001	-0.00053	0.115318	0.008208	0.195441

Discussion

Wheat is a crucial cereal crop with a significant role in current and future food security. Among abiotic stresses, drought stress is a major factor limiting the growth and production of wheat. K is recognized as a vital stress-alleviating nutrient for wheat under TDC (Basit *et al*., 2023). Our findings indicate that applying K in water deficit conditions enhances growth and production in wheat among the studied parameters. Plant height positively increased in Ghazi 2019 in the normal irrigated condition. Under TDC, Ghazi-2019 and Dilkash-2021 showed the maximum response. It indicates that K markedly alleviates the negative impact of drought in these genotypes. Similar results have been recently reported in the literature (Ahmad *et al*., 2022; Sarwar *et al*., 2023), who found that water stress negatively affects growth parameters, especially plant height, by disrupting water status and chlorophyll pigments. This disruption has a direct effect on stomatal conductance and photosynthetic efficiency.

However, foliar application of K played an important role in ameliorating the negative effects of water stress. The effectiveness is highly dependent on the concentration of K applied, as shown in the results. Drought stress adversely impacted peduncle length of wheat genotypes, with considerable variations noted in response to K application (Chowdhury *et al*., 2021). Showcased a significant positive response to the applied treatment under normal irrigated conditions. In situations of water deficit, Akbar-19 resulted the highest response. A study observed similar outcomes in their research (Hashmi *et al*., 2023).

The spike length and the number of spikelets per spike in wheat genotypes are significantly impacted by drought stress. Dilkash-2021 demonstrated a substantial improvement in both spike length and the number of spikelets per spike through K application, showing noteworthy responsiveness under both normal watering conditions and drought stress. Ayyub *et al*. (2024) reported consistent results in their research, aligning with the findings mentioned above. Drought profoundly influences both the physiology and morphology of plants, given the crucial role of water in facilitating the proper transportation of nutrients. The scarcity of water disrupts the normal flow of nutrients, leading to a reduction in spike length and the number of spikelets. K plays a pivotal role in osmotic and nutritional movement within the plant. Consequently, it has the potential to enhance these parameters. The results indicate a significant improvement in growth with K application (Sardans & Peñuelas, 2021).

Our findings reveal that the imposition of drought had a detrimental impact on the flag leaf area in wheat genotypes. However, the application of K demonstrated a positive effect on the flag leaf area across the genotypes. Notably, Akbar-19 exhibited the maximum flag leaf area under both drought and normal irrigation conditions. Hashmi *et al*. (2023) recently documented analogous outcomes in their literature findings. Drought stress disrupts the growth of the flag leaf by impacting various plant mechanisms, including the reduction of cell expansion (Wahab *et al*., 2022).

The scarcity of water leads to closed stomata, resulting in decreased gaseous exchange and a lower rate of photosynthesis in the leaf. K plays a crucial role in essential mechanisms such as osmotic adjustment, stomatal regulation, and gaseous exchange, ensuring the structural integrity of the leaf. K activation of various enzymes supports sustained photosynthesis and energy production (Basit *et al*., 2023). Consequently, K exhibits the potential to enhance the overall flag leaf area in wheat under drought stress, as evidenced by our results.

Our results shown that the imposition of drought adversely impacted the number of tillers in wheat genotypes. Conversely, the application of K demonstrated a positive influence, enhancing the number of tillers across the genotypes. Notably, the maximum value was observed in Akbar-19 in normal irrigated conditions, and in Faisalabad-2008 under TDC. Moghal *et al*. (2020) reported a favorable effect of K on morphological characters, specifically the number of tillers in wheat, under water-stressed conditions.

K plays a pivotal role in root development, significantly enhancing the plant's capacity to access water and overall performance. This improvement extends to morphological characteristics such as the number of tillers, spike length, number of spikelets, and flag leaf area, ultimately positively influencing complex yield traits. Concurrently, K actively regulates plant hormones, and our results demonstrate that optimal concentrations, exemplified by the K application, positively affect hormone regulation. K treatment enhances auxin regulation, fostering the development of lateral buds into tillers (Basit *et al*., 2023; Hashmi *et al*., 2023; Pettigrew, 2008).

The 1000 Grain Weight stands as a crucial measure, quantifying the average mass of individual grains in wheat crops (Kim *et al*., 2021). The results exhibited a substantial decrease in the thousand grain weight in the genotypes subjected to drought stress in our experiment. K emerged as a significant factor in enhancing the thousand-grain weight across the genotypes. The findings highlighted the maximum improvement in Subhani-2021 and Ghazi-21 under normal and TDC, respectively. Similarly, reported a positive increase in the 1000 grain weight of wheat at the highest K rate employed in their experiment (Aouz *et al*., 2023). Grain yield, representing the ultimate output of a plant, is the most crucial and comprehensive character we measured. It serves as a complex trait influenced by a myriad of factors, with all other plant characteristics collectively exerting their influence on it (Montgomery, 2021). The highest grain yield was observed in Faisalabad-2008 in irrigated conditions.

Conversely, under water deficit conditions, the maximum grain yield was recorded in Akbar-19. Amjad *et al*. (2021); Dawood *et al*. (2021). concur in their findings, demonstrating that K enhances the overall yield of wheat genotypes under drought stress by improving various plant mechanisms. Drought stress, by disrupting the overall normal functioning of the plant and negatively impacting physiological and morphological processes, imposes limitations on the final yield across all genotypes. The foliar application of K exerts a positive influence on the yield per plant of wheat genotypes under drought stress. K operates by enhancing various mechanisms, encompassing osmotic adjustment, hormone regulation, nutrient uptake, maintenance of photosynthetic rate, and overall stress tolerance. These improvements collectively contribute to an enhanced overall yield in the wheat genotypes (Basit *et al*., 2023; Choudhary *et al*., 2021).

CONCLUSION

The experimental results revealed that soil application of K enhances the yield of wheat in both irrigated and drought field. Higher K concentrations led to an increase in yield. Application of K did not yield significant results for traits such as the number of spikelets and peduncle length. In general, the application of K led to enhanced growth and increased yield of wheat. Plant height, spike length, number of spikelets, flag leaf area, yield per plant, and 1000-grain weight were found positively correlated with yield and have positive direct effect on yield. K3 may be deemed more suitable for enhancing wheat productivity. Akbar-19 genotype was superior most for grain yield under K3 concentration in drought condition. The combination of varietal selection and K fertilization holds promise as a viable strategy for enhancing both the productivity and quality of wheat.

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AUTHOR CONTRIBUTIONS

The authors contributed equally to this study.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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