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## Research Article

# Characterizing Drought Tolerance in Wheat Genotypes for Yield Associated Traits Under Different Water Stress Conditions

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## ABSTRACT

For agriculture to improve crop performance, drought resistance was identified as a crucial breeding goal. During the Rabi season, this research evaluated six F<sub>2</sub> segregating wheat progenies for grain production and related traits in both normal and water-stressed conditions. The plants had to respond to three different water treatments: T<sub>1</sub> included regular irrigations, T<sub>2</sub> involved one irrigation that escaped during the tillering stage, and T<sub>3</sub> involved one irrigation that escaped during the booting stage. The variance analysis of traits such as tiller number m<sup>-2</sup>, panicle length (cm), grain yield per plant (g), harvest index, and osmotic potential (-MPa) of the six F<sub>2</sub> segregating populations and their parent wheat varieties was significant ( $P \leq 0.05$ ). Plant height (cm), number of spikelets (number per spike), number of grains (number per spike), thousand-grain weight (g), biological yield (kg ha<sup>-1</sup>), and grain yield (kg ha<sup>-1</sup>) are significant at  $P \leq 0.01$ . The T<sub>2</sub> and T<sub>3</sub> offspring of TD-1 × Imdad, Sarsabz × Khirman, and Kiran-95 × Khirman showed higher plant height, tiller number, spikelet number, panicle number, biological yield, yield kgha<sup>-1</sup>, thousand-grain weight, and harvest index. Hybrids TD-1 × Imdad, TJ-83 × Khirman, Sarsabz × TJ-83, and Sarsabz × Khirman showed excellent performance under stress during the tillering stage, with Sarsabz × TJ-83 showing high grain production per plant. The total performance of the F<sub>2</sub> progenies might be more favorable for selection under water stress conditions at various growth stages.

**Keywords:** Drought tolerance, grain yield, morphological traits, physiological traits, wheat.



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## INTRODUCTION

Drought stress tolerance is exhibited by nearly all plants, though its extent varies among species and even within the same species. Water deficit and salt stress are worldwide problems that affect the survival of agricultural crops and the sustainability of food supply (Jaleel et al., 2007). Climatic variations have resulted in hot and dry summers, adversely affecting many crop plants (Foulkes et al., 2007). With ongoing global climate change, increasing water scarcity, and a deteriorating

ecological environment, wheat production is significantly impacted (Singh and Chaudhary, 2006). Wheat (*Triticum aestivum* L.), a staple food for Pakistan and nearly 35% of the global population (Sial et al., 2009), is experiencing increasing demand. However, its productivity is being hindered by environmental challenges. Boosting yield potential is essential for combating global hunger. However, drought stress has been observed to significantly impact grain yield, with losses estimated between 17% and 70%, making it a critical concern. Rising temperatures lead to increased CO<sub>2</sub> levels, and if these exceed threshold limits, crop yields decline accordingly (Singh et al., 2014; Kubar et al., 2025a). High temperatures directly impact wheat growth stages, from anthesis to maturity, potentially accelerating or delaying leaf senescence, reducing average kernel weight, and ultimately affecting yield (Sial et al., 2009). The ability of wheat to tolerate varying moisture stress conditions can help bridge the productivity gap in irrigated wheat crops (Munir et al., 2007; Kubar et al., 2025b). Therefore, research is essential to develop wheat strains capable of withstanding high temperatures while maintaining high yield potential and quality traits. Drought remains a significant challenge in many regions where wheat, barley, and other small-grained cereals form staple diets.

One of the main goals of crop breeding is to get plants to produce a lot of food even when they are under a lot of stress from drought (Blum, 1988; Kaleri et al., 2024(a)). Breeding strategies have been believed for over 80 years to hold the potential to bridge the yield potential gap and develop improved wheat strains (Cattivelli et al., 2008). Traditional breeding methods, marker-assisted breeding (MAB), and genetic engineering have all been shown to increase wheat yield in places that are prone to drought (Ashraf, 2010). Each growth stage of wheat plays a crucial role in achieving optimal yield, from tillering to the grain-filling period. The crop is highly sensitive to heat shocks and temperature extremes, which negatively impact its productivity. Therefore, various selection methods can be employed to enhance drought tolerance and improve grain yield. Previous research has shown that choosing high-yielding genotypes can help with cultivation in both wet and dry conditions (Sio-Se Mardeh et al., 2006; Kaleri et al., 2024b).

As an alternative, selecting secondary traits that contribute to drought resistance or tolerance can increase yield in water-limited environments and make them useful for current breeding programs (Ganapathy and Ganesh, 2008; Kaleri et al., 2023). Future developments in improving drought resistance or tolerance may be made by focusing on certain features that increase the harvest index or crop water-use efficiency. Increased competition with weeds for water and nutrients is another benefit of rapid early leaf area expansion, which also accelerates eventual crop growth rates. Furthermore, choosing low-delta cultivars has been shown to boost production in drought-stressed environments. The enhancement of yield in small-grain crops is also thought to depend on a number of constitutive and induced features, including phenology, leaf xeromorphy, excised-leaf water loss, rooting behaviour, leaf senescence, and stored assimilates. Because traditional techniques are time-consuming and rely on genetic diversity that already exists, traditional plant breeding procedures have turned toward physiological selection requirements (Zhu, 2002).

Tolerance to abiotic stresses is hard to figure out because stressors and the molecular, biochemical, and physiological processes that affect plant growth and development work together in complex ways (Roza and Khayatnezhad, 2010). In our study, we focused on utilizing selected valuable genotypes and interspecific crosses of parent lines. Ashraf (2010) suggests that intercrossing can lead to the development of new gene combinations, incorporating desirable traits and generating variability in the offspring. The selected parent lines and newly developed cross combinations were evaluated under both drought-stressed and non-stressed conditions. Irrigation was withheld at different growth stages of wheat, as previous studies suggest that reducing irrigation duration during the crop cycle can be beneficial under varying environmental conditions (Cattivelli et al., 2008).

## MATERIAL AND METHODS

### An interspecific crosses and genotypes selected

Pakistani genotypes, including Imdad, TD-1, Kiran-95, Khirman, Sarsabz, and TJ-83, were selected for quality and yield traits. Crossed with other genotypes, six valuable combinations were developed, proving prone to growth under different wheat irrigation stages and stress and non-stress conditions.

### Experimental Site, design implied and different irrigation treatment applied

This research analyzed wheat genotypes at Latif Farm, SAU, Tando Jam, over two years. The genotypes were exposed to three water treatments using a randomized block, split-plot design. Important cultural practices were consistently implemented throughout the growing period. The experiment was repeated three times, with the same irrigation treatments applied to cross combinations/offspring. The study aimed to evaluate the performance of wheat genotypes under irrigation omission at critical growth stages.

### Agronomical measurements observed

The study measured various morphological traits of wheat plants, including tillers per square meter, plant height, spike length, spikelets per spike, grains per spike, 1000-grain weight, grain yield per plant, biological yield, grain yield, and harvest index. The total number of tillers was counted at maturity, and the number of fertile tillers per plant was recorded for each replication within the treatment. The number of grains per spike was assessed by counting seeds from five randomly selected spikes, and the weight of one thousand grains was measured using an electronic balance. After harvest, each plant was individually threshed, and the cleaned seeds were collected for grain yield measurement. The biological yield and grain yield were calculated using formulas. The harvest index was calculated as the ratio of seed yield divided by total dry matter  $\times 100$ .

### Physiological parameters observed

The study assessed osmotic adjustment in leaf sap using an osmometer, and analyzed the extracted sap. The relative water content was determined by collecting leaves, determining fresh and turgid weights, and oven-drying turgid leaves. The relative water content was calculated using a formula from Schonfeld et al. (1988).

### Statistical analysis

ANOVA was used to analyse the data, and these formulas were used to get the Least Significant Difference (LSD) and the standard error of the difference between means (SED).

$$SED = \sqrt{\frac{2EMS}{n}} \quad SED = \sqrt{\frac{2EMS}{n}}$$

$$LSD = SED \times t(0.05)_{df} \quad LSD = SED \times t(0.05)_{df}$$

## RESULTS

### Different Traits' Effective Response to Stress and Non-Stress Water Conditions.

The ANOVA results for the characteristics of the six  $F_2$  segregating populations are presented in Table 1.

Table 1. Pooled Analysis of variance (ANOVA) of quantitative and qualitative traits of wheat (*Triticum aestivum* L.) genotypes under normal and water stress conditions

Source of variation	Mean of squares													
	Df	No. of Tiller /m <sup>2</sup>	Plant height (cm)	Spike length (cm)	No. of Spikelets/ spike	No. of grain/ Spike	100 grain wt (g)	Grain yield/ plant (g)	Biological Yield Kg/ha	Grain yield Kg/ha	Harvest Index (%)	Osmotic potential (- MPa)	Relative water content (%)	Leaf area (cm <sup>2</sup> )
Replications	2	9330.28	39.69	0.16	0.2973	14.685	6.63	0.18	456734	107923	10.534	1.76720	1.023	2.5326
Treatments water (T)	2	9259.79*	65.672**	1.77*	0.3304**	283.10**	33.68*	0.07*	2668746**	450545**	25.711*	5.55993*	75.212**	1.1759**
Error	4	9446.19	29.15	0.09	2.4269	45.32	9.88	0.06	269051	10128	24.066	3.92734	0.685	0.7688**
Varieties (V)	1	9394.98*	224.78**	0.52*	7.6983**	86.58**	27.76*	0.12*	3825399**	347254**	172.762*	2.82979*	181.314**	40.9926**
Treatments x Varieties (TxV)	2	9268.62*	158.72**	0.12*	3.8739**	138.35**	2.41**	0.085*	582191**	154147**	14.574	3.13204*	36.169**	7.491**
Error	4	288.70	14.87	0.37	1.0775	41.191	4.36	0.081	28880	52704	13.712	3.135	3.363	1.478

\*\* = Significant at  $P \leq 0.01$ , \* = Significant at  $P \leq 0.05$ .

The T represents the water treatments applied, V is for genotypes/varieties used and T x V is the interaction between treatment of water and genotypes

The findings revealed a significant difference ( $P \leq 0.05$ ) among genotypes and treatments for various traits under water stress conditions. Additionally, a highly significant genotype-by-environment interaction ( $G \times E$ ,  $P \leq 0.01$ ) was observed (Table 1). Mean squares from ANOVA under water stress conditions for the six  $F_2$  segregating populations and their parental wheat varieties showed significant differences ( $P \leq 0.05$ ) for traits such as the number of tillers per square meter, spike length (cm), grain yield per plant (g), and harvest index. Meanwhile, plant height (cm), number of spikelets per spike, number of grains per spike, 1000-grain weight (g), biological yield ( $\text{kg ha}^{-1}$ ), and grain yield ( $\text{kg ha}^{-1}$ ) exhibited highly significant differences at the  $P \leq 0.01$  probability level (Table 1). Similarly, previous studies have reported substantial variation among genotypes and treatments for multiple phenotypic traits (Sial et al., 2010). Osmotic potential (-MPa) showed significant variation at  $P \leq 0.05$ , whereas leaf area ( $\text{cm}^2$ ) and relative water content were highly significant at the  $P \leq 0.01$  level (Table 1). These results are in line with earlier studies that showed how important physiological traits are in both wet and dry environments (Khakwani et al., 2012).

### **Variations in agronomic characteristics that indicate drought tolerance in wheat genotypes and their progenies**

Many types of plants possess the capacity to tolerate a variety of stresses, both biotic and abiotic. But wheat is a grain that many people throughout the world consume every day and is obviously necessary for a huge population. Therefore, it is necessary to produce such dependable genotypes that can endure the growing worldwide climate with the objective of increasing production. The selection of key traits for stress escape, avoidance, or tolerance, as well as the breeding strategy for drought stress, depends on the intensity and duration of stress in the target environment. Our findings revealed that different genotypes and progeny exhibited varying performances under both water-stressed and non-stressed conditions. Different types of plants and their offspring did their best in terms of things like plant height (cm), spike length (cm), number of spikelets per spike, number of grains per spike, 1000-grain weight (g), grain yield per plant (g), biological yield ( $\text{kg ha}^{-3}$ ), grain yield ( $\text{kg ha}^{-3}$ ), and harvest index when the T1 treatment was used as the control. ent included five regular irrigations, ensuring consistent water availability throughout the wheat growth process without any water deficiency at any stage.

There was significant variation in the traits of T2 and T3, however, since one water irrigation was lost during the tillering and booting stages, respectively. All six  $F_2$  progenies—TD-1 x Imdad, Sarsabz x TD-1, T.J-83, Khirman, Sarsabz x T.J-83, and Sarsabz x Khirman—exhibited a significant increase in plant height (cm) under normal irrigation (T1) as compared to their parent lines (111.6, 98.66, 96.4, 89.9, 96.0, and 86.0, respectively). (Figure 1). All of the same progenies showed higher numbers of tillers  $\text{m}^{-2}$ , with the exception of Sarsabz x Khirman, who contributed less tillers  $\text{m}^{-2}$  in T1 (421) (Figure. 2). The progenies TD-1 x Imdad, Sarsabz x TD-1, and Sarsabz x T.J-83 have shown a substantial ( $P \leq 0.01$ ) increase in the attributes spike length (cm), number of grains spike $^{-1}$ , and spikelets spike $^{-1}$  when compared to their respective parental lines at T1 (Table 1). The six progenies did well overall in terms of grain yield plant $^{-1}$  (g) (Figure. 6). However, T1's biological production ( $\text{kg ha}^{-1}$ ) was larger because of the contributions of TD-1 x Imdad, T.J-83 x Khirman, and Sarsabz x Khirman (7291, 6666, and 6458) (Figure. 7). With the exception of Kiran-95 x Khirman, all of the progenies performed better for the attributes of grain yield ( $\text{kg ha}^{-1}$ ), 1000-grain weight (g), and harvest index with regular irrigations (Figure. 8, 9, 10). During the progenies' escape of one irrigation during the tillering (T2) and booting stages (T3), a notable variance was seen. The maximum plant height (cm) was impacted by T.J-83 x Khirman and Kiran-95 x Khirman (78.6, 73.2) in T3 and T.J-83 x Khirman and Sarsabz x T.J-83 (84.6, 81.6, 79.0) in T2 (Figure. 1). Compared to for tillers  $\text{m}^{-2}$ , Kiran-95, Khirman, and Sarsabz x TD-1 did well in T2 and T3 (Figure. 2). The progenies T.J-83 Khirman, followed by Sarsabz x TD-1, showed highly important results in T2 for spike length (cm), grain spike $^{-1}$  (g), spikelets spike $^{-1}$ , grain yield plant $^{-1}$  (g), and 1000-grain weight (g) (Fig 3-6, 9). whereas Sarsabz x TD-1 and TD-1 x Imdad showed significant improvements to harvest index (35.0, 41.0 Figure. 10), grain yield ( $\text{kg ha}^{-1}$ ) (11774, 2145 Figure. 8), and biological yield ( $\text{kg ha}^{-1}$ ) (15416, 4999 Figure. 7). The progenies of TD-1 x Imdad did very well for spike length (cm) (8.9) and grain spike $^{-1}$  (35) in T3. In contrast, traits such as spikelets spike $^{-1}$ , grain yield plant $^{-1}$  (g), and grain yield ( $\text{kg ha}^{-1}$ ) were better performed by the progenies T.J-83 x Khirman and Kiran-95 x Khirman in T3 (Figures. 5, 6, 8). As a result, under stress, distinct progenies showed differences in several characteristics, which increased yield.

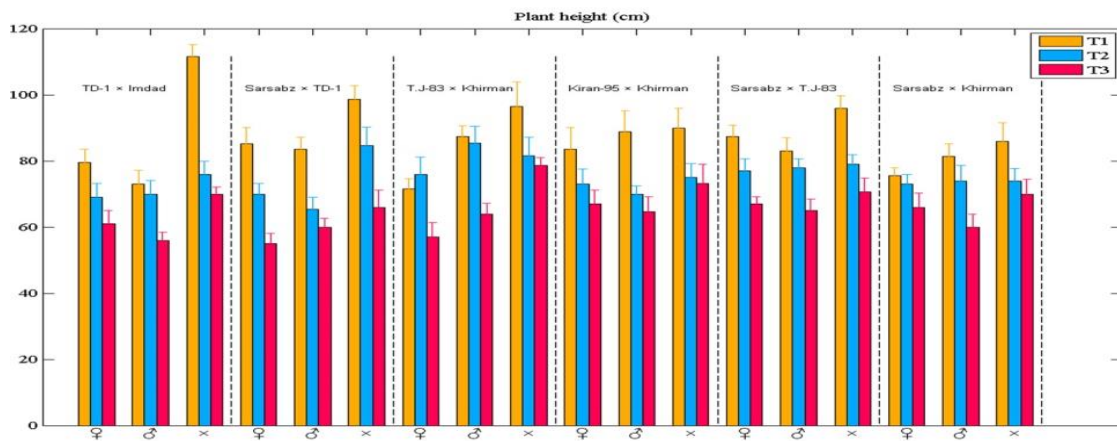


Figure 1. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait plant height (cm) at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

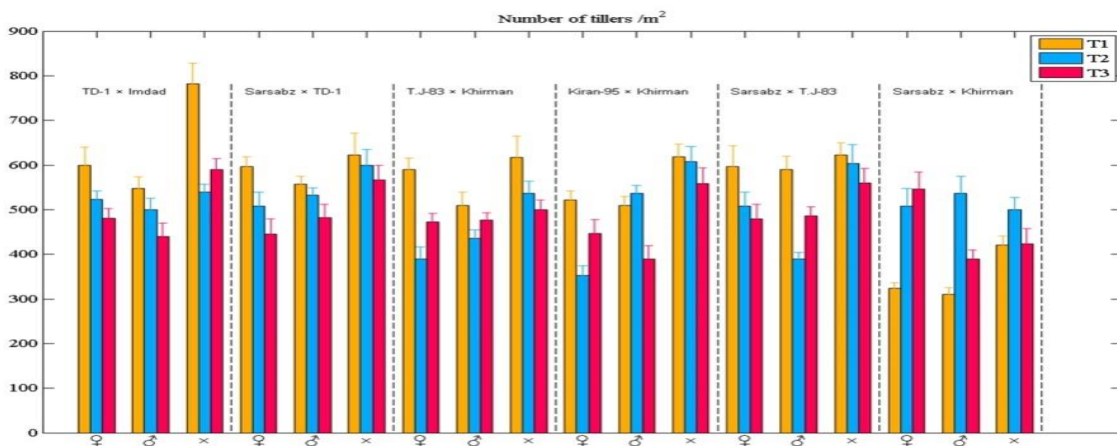


Figure 2. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait number of tillers/m<sup>2</sup> at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

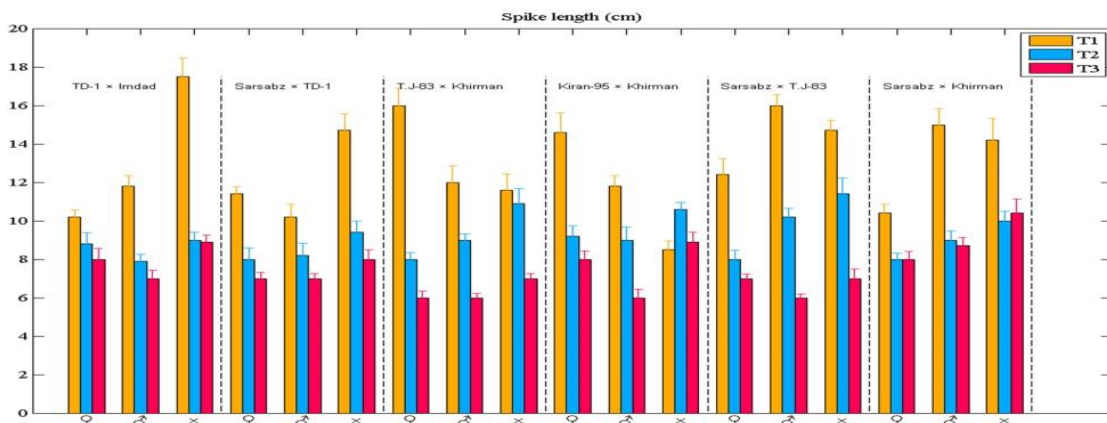


Figure 3. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait spike length (cm) at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

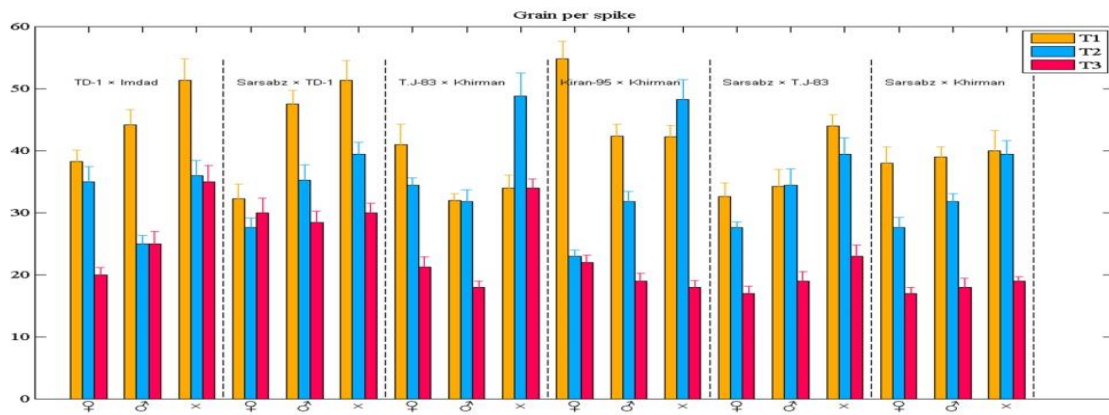


Figure 4. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait grains spike<sup>-1</sup> at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

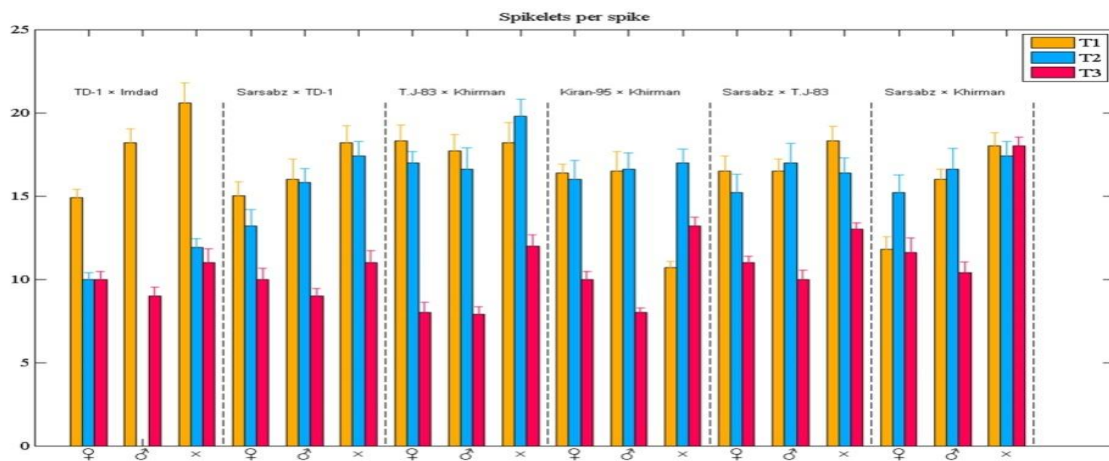


Figure 5. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait spikelets spike<sup>-1</sup> at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

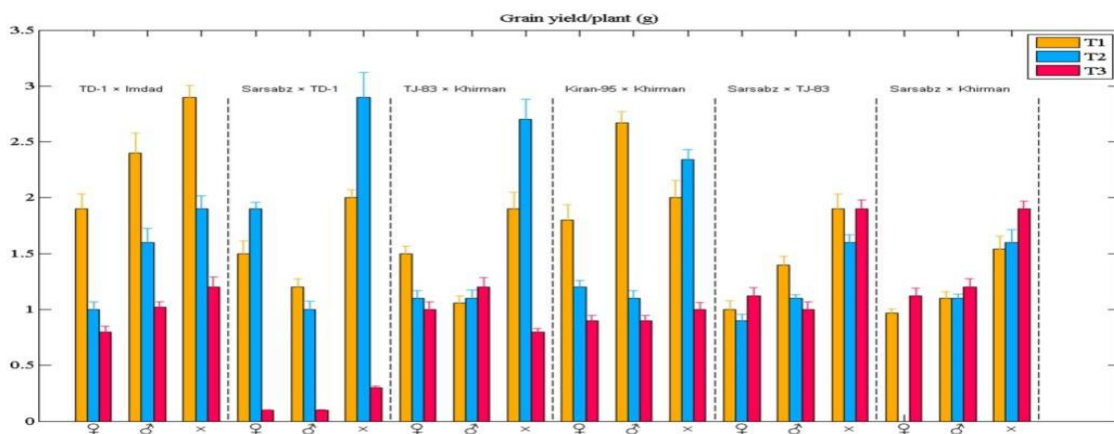


Figure 6. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait grain yield plant<sup>-1</sup> (g) at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

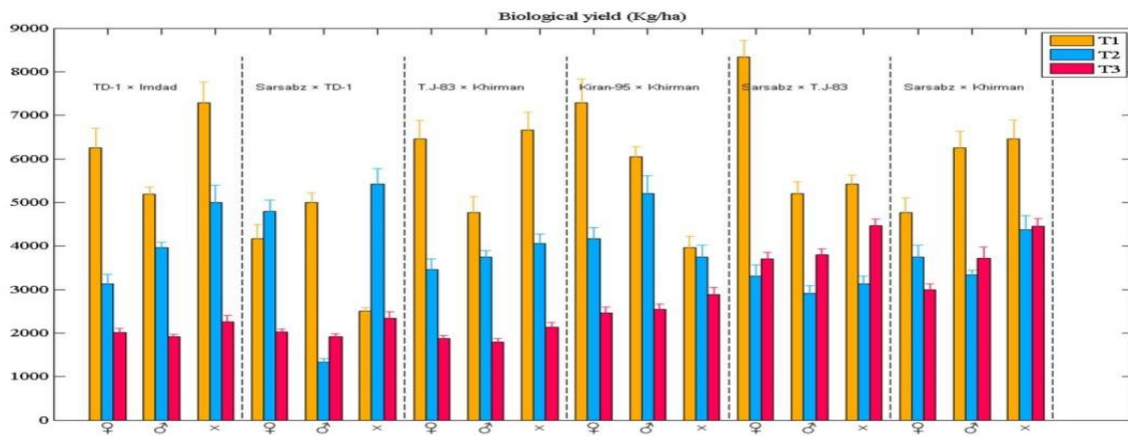


Figure 7. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait biological yield kg ha<sup>-1</sup> at different irrigations. T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

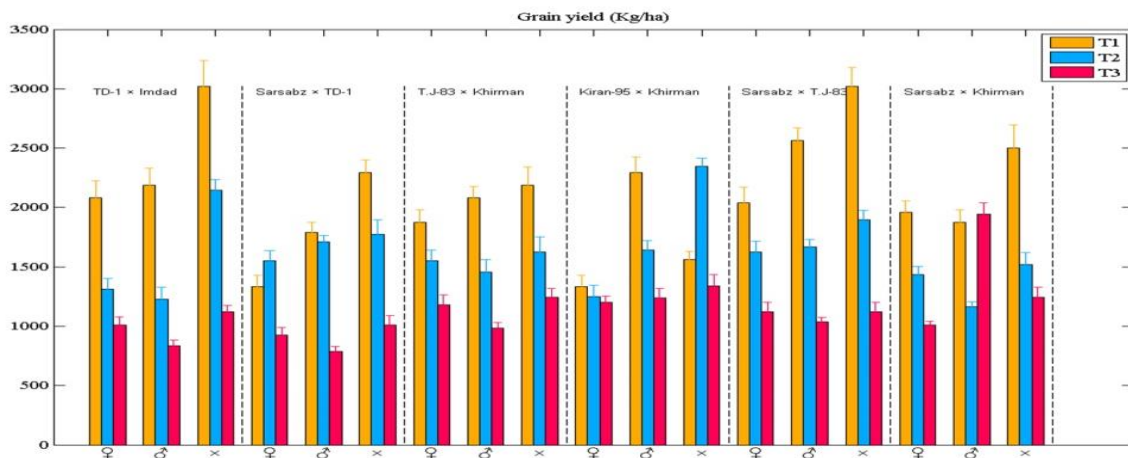


Figure 8. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait grain yield kg ha<sup>-1</sup> at different irrigations. T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

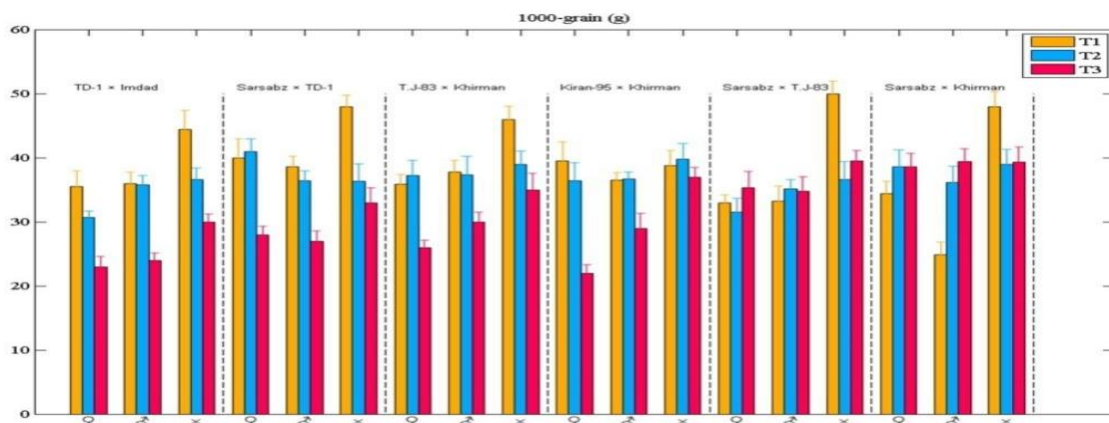


Figure 9. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait 1000 grain wt (g) at different irrigations. T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

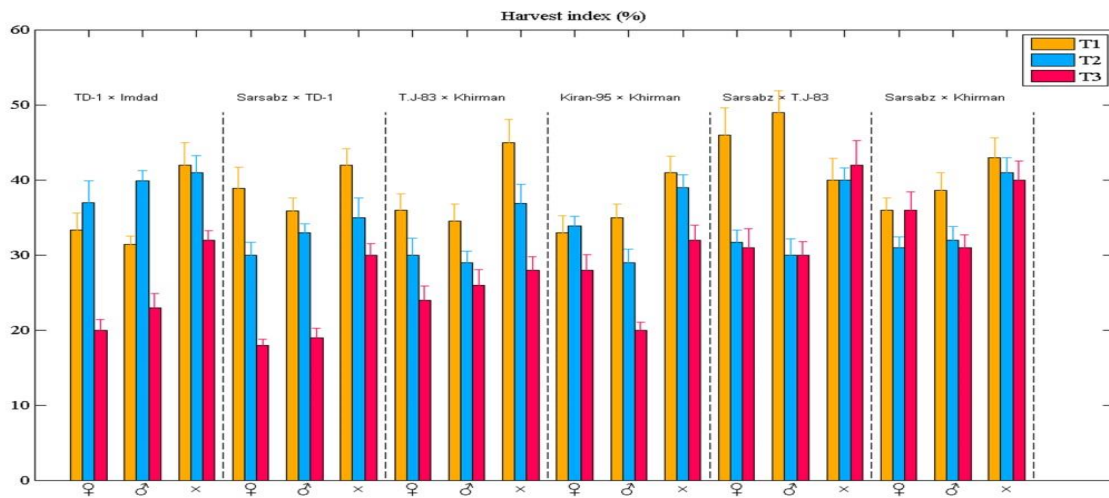


Figure 10. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait harvest index (%) at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

**Physiological traits observed during stress conditions**

Compared to water content, leaf water potential (cm<sup>2</sup>) are two physiological characteristics that are useful for analysing how crops react to water stress (Siddique et al., 2000). According to our findings, a significant decrease in the physiological features of F<sub>2</sub> progenies was seen in T2 and T3 as compared to the standard irrigation (T1) (Table 2). However, a majority of the progenies altered the three physiological features in typical situations during T1 (Table 2). Kiran-95 × Khirman and Sarsabz × TD-1 were observed to have larger leaf areas (cm<sup>2</sup>) than other progenies (28, 26) in T1 (Figure. 12). This was similar to the findings for leaf area (cm<sup>2</sup>). Sarsabz × T.J-83 had superior osmotic potential (-MPa) in these progenies, followed by Kiran-95 × Khirman (Figure. 13). However, the dry conditions during T2 and T3 had an impact on the progenies, and in various progenies, the three physiological parameters were significantly reduced. But compared to other progenies in T2, some of them, such as T.J-83 × Khirman and Kiran-95 × Khirman, had superior relative water content percentages and leaf area (cm<sup>2</sup>). Sarsabz × TD-1 indicated greater osmotic potential in T2 and T3 for osmotic potential (-MPa) (Figure. 13). As a result, under drought conditions, Sarsabz × Khirman and Sarsabz × T.J-83 (19.9, 19.7) performed better than the others in T3 for relative water content and leaf area (cm<sup>2</sup>), respectively (Figures. 11, 12).

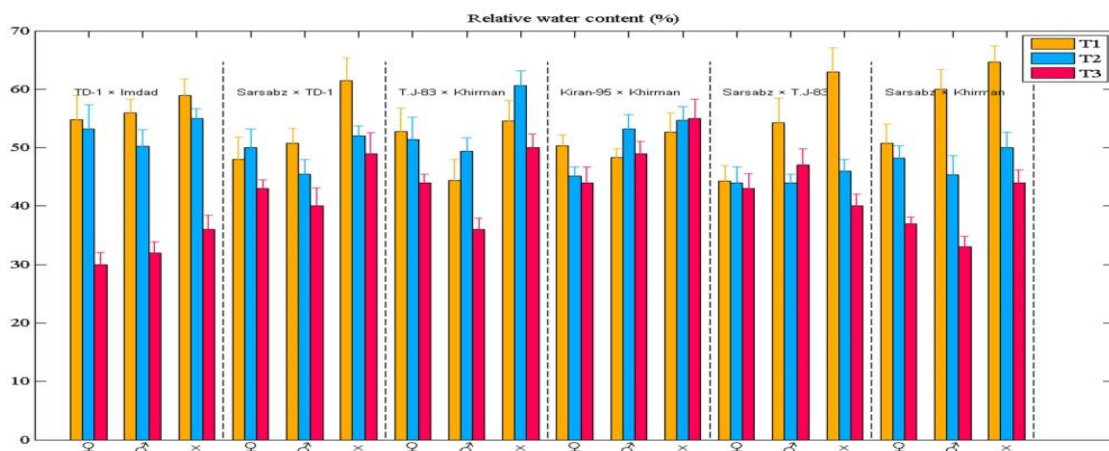


Figure 11. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait relative water content (%) at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

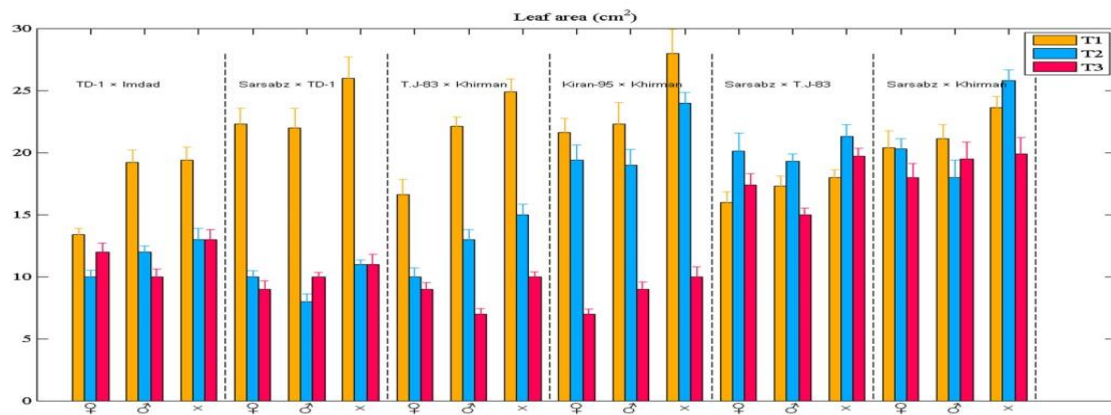


Figure 12. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait leaf area (cm) at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

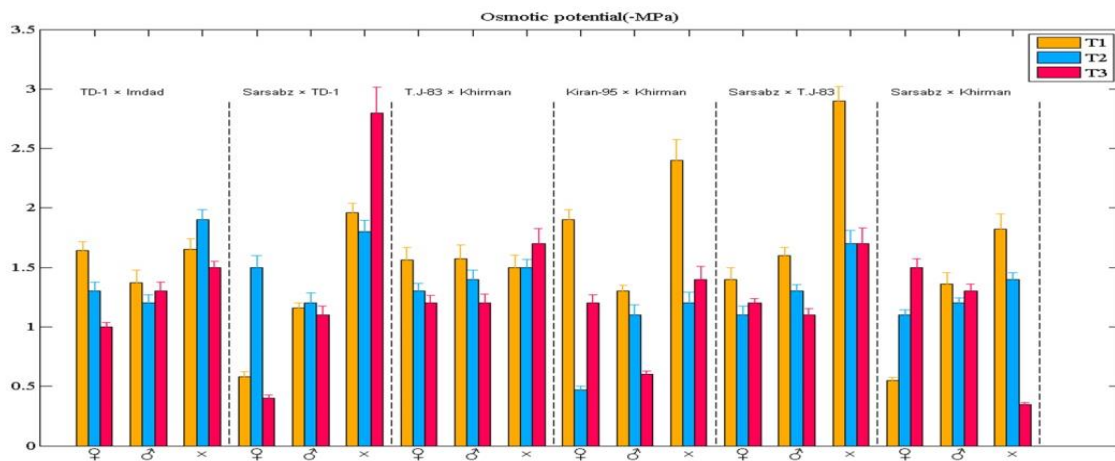


Figure 13. Mean performance of six F<sub>2</sub> progenies and their respective parental lines of wheat for the trait osmotic potential(MPa-) at different irrigations.

T1: normal irrigation, T2: escape of irrigation at tillering stage and T3: escape of irrigation at booting stage.

### DISCUSSION

In Pakistan, wheat, a staple food that is extensively suitable for one-third of the world's population, grows successfully in the hottest, warmest conditions. Cultivars with high yield potential are required to satisfy population needs. A significant breeding goal for improving agricultural performance is drought resistance. Researching the physiological, cellular, biochemical, and molecular processes of drought tolerance might provide light on various adaptation options. This research was carried out over the course of two years, during the Rabi season of 2011–12 and 2012–13, at Sindh Agriculture University's Latif Farm in Hyderabad, Pakistan. Three water treatments—normal irrigation, drought exposure, and booting—were implemented using a split plot design. Six genotypes were included: Sarsabz, Kiran-95, Imdad, TD-1, Khirman, and T.J-83. Various physiological and agronomic traits were applied. Selection using yield and its components is more successful than selection only on yield, according to earlier research. Morphological, physiological, and developmental traits are more effective in enhancing drought tolerance in genotypes, and segregating hybrids may provide more value. Table 1 Under water stress treatments, the research identified significant ANOVA findings for a number of characteristics in six F<sub>2</sub> segregating populations and their parent wheat types. These characteristics included osmotic potential, harvest index, grain yield, spike length, and number of tillers. Other important factors were plant height, number of spikelets, number of grains, biological yield, grain yield, relative water content, and leaf area. Different irrigation methods caused big differences in the average performance of many traits, which had an impact on genotypes at different growth stages.

Under control conditions (T1), five of the six progenies—TD-1 × Imdad, Sarsabz × TD-1, TJ-83 × Khirman, Sarsabz × TJ-83, and Sarsabz × TJ-83—showed greater plant height as compared to their respective parent lines. The research examined how different traits performed in various irrigation regimes, which had an impact on genotypes at different times. height, while Kiran-95 × Khirman had an average greater plant height. considerable drop in trait plant height under water stress. phases of drought stress shortened the crop's typical growth times. average greater plant height, whereas five progenies—TD-1 × Imdad, Sarsabz × TD-1, TJ-83 × Khirman, Sarsabz × TJ-83, and Sarsabz × TJ-83—performed better for trait plant height under control conditions (T1). Progenies showed a significant reduction in trait plant height when exposed to water stress. Stress at various stages shortens the crop's typical growth phases. stress, however, all progenies showed a considerable drop in trait plant height. Phases were shortened by drought stress at various stages. The Sarsabz × TD-1, TJ-83 × Khirman, and Sarsabz × TJ-83 hybrids showed more tillers, spikelets, grains, grain yield, biological yield, grain yield  $\text{kg ha}^{-1}$ , and 1000 grain weight compared to other progenies. However, some progenies were affected by reduced yield, as drought stress reveals high heritability but is associated with less yield. The hybrids TD-1 × Imdad, T.J-83 × Khirman, Sarsabz × T.J-83, and Sarsabz × Khirman performed exceptionally well under stress during the tillering stage for grain yield ( $\text{kg ha}^{-1}$ ), biological yield ( $\text{kg ha}^{-1}$ ), and 1000-grain weight (g) (Figures. 7, 8, 9). The harvest index and relative water content (RWC%) were higher in TD-1 × Imdad and Kiran-95 × Khirman (Figures. 10 and 11).

During this stage, leaf area ( $\text{cm}^2$ ) decreased in several progenies, including Sarsabz × TD-1, T.J-83 × Khirman, and Sarsabz × T.J-83 (Figure. 12). However, Sarsabz × Khirman and Kiran-95 × Khirman once again demonstrated superior yield performance for biological yield ( $\text{kg ha}^{-1}$ ), grain yield ( $\text{kg ha}^{-1}$ ), and 1000-grain weight (g), along with TD-1 × Imdad (Figures. 7, 8, 9). Stress conditions decrease traits like relative water content, leaf area, grain number, tiller number, grain yield, and biological yield. We halted irrigation during booting in T3, leading to a significant decrease in these traits. However, three progenies, TD-1 × Imdad, Sarsabz × TD-1, and Kiran-95 × Khirman, maintained taller plant heights (70, 78.6, and 73.2 cm, respectively) (Figure. 1). The Sarsabz × TJ-83 hybrid outperformed other progenies in traits like tiller number, spikelet number, grain number, and grain yield per plant (Figures. 7, 8, 9). Additionally, Sarsabz × T.J-83 and Kiran-95 × Khirman outperformed others in the harvest index (Figure. 10). The harvest index is crucial for identifying drought-resistant genotypes in stressful environments, but physiological traits like leaf area declined significantly in Sarsabz × TD-1, TJ-83 × Khirman, and Kiran-95 × Khirman (Figure. 12). Sarsabz × TJ-83 and Sarsabz × TD-1 had higher osmotic potential, which suggests they could be drought-tolerant hybrids. On the other hand, Kiran-95 × Khirman had lower osmotic potential (Figure. 13). Similar findings have been reported in wheat cultivars with increased leaf osmotic potential under drought stress (Gupta et al., 2001). The study found that certain wheat hybrids, such as TD-1 × Imdad, Sarsabz × TJ-83, and Sarsabz × Khirman, maintained higher yields despite minimal water stress during the tillering and booting phases. This suggests that selecting parental lines with high yield potential can produce progenies with improved drought resistance and yield performance under water-limited conditions. Identifying adaptable genotypes and hybrids for various drought stress stages is essential for future breeding programs. Researchers have emphasised the importance of using wild relatives' allelic diversity to enhance drought tolerance in wheat. Proper characterisation of existing genetic collections at morphological, physiological, and molecular levels is necessary to achieve this goal. The hybrids showed superior performance in plant height, number of tillers per square meter, spikelets per spike, number of grains per spike, grain yield, biological yield, and 1000-grain weight. However, physiological traits, including leaf area and osmotic potential, significantly decreased in Sarsabz × TD-1, TJ-83 × Khirman, and Kiran-95 × Khirman. These results highlight the potential of certain wheat hybrids for improved drought tolerance and productivity under water-limited conditions.

## CONCLUSIONS

Drought stress tolerance is crucial for agricultural crops, particularly wheat, which faces challenges due to global climate change, water scarcity, and environmental degradation. High temperatures can significantly impact grain yield, affecting growth stages and kernel weight. Research is needed to develop wheat strains that can withstand high temperatures while maintaining high yield potential. Crop breeding aims to boost wheat yield in drought-prone areas using traditional methods, marker-assisted breeding, and genetic engineering, enhancing drought tolerance and water-use efficiency. This research evaluated six F2 segregating wheat progenies during the Rabi season for grain production and related traits under normal and water-stressed conditions. The plants were subjected to three different water treatments: regular irrigations, one irrigation that escaped during the tillering stage, and one irrigation that escaped during the booting stage. The variance analysis revealed significant differences in traits such as tiller number, panicle

length, grain yield per plant, harvest index, and osmotic potential. The T2 and T3 offspring of TD-1×Imdad, Sarsabz×Khirman, and Kiran-95×Khirman showed higher plant height, tiller number, spikelet number, panicle number, biological yield, yield kg ha<sup>-1</sup>, thousand-grain weight, and harvest index. Hybrids TD-1 × Imdad, TJ-83 × Khirman, Sarsabz × TJ-83, and Sarsabz × Khirman showed excellent performance under stress during the tillering stage, with Sarsabz × TJ-83 showing high grain production per plant. The total performance of the F2 progenies might be more favorable for selection under water stress conditions at various growth stages.

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## AUTHOR CONTRIBUTIONS

All the authors contributed equally to this research.

## COMPETING OF INTEREST

No conflicts of interest have been disclosed by the authors.

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