RESILIENCE UNVEILED: EXPLORING DROUGHT-RESILIENT WHEAT VARIETIES' ADAPTATIONS TO SALINITY STRESS

BHUTTO, L. A.[1] – OSBORNE, C. P.[2] – QUICK, W. P.[2] – SALEH, I. A.[3] – ABDEL-MAKSOUD, M. A.[4] – EL-TAYEB, M. A.[4] – ABRO, A. A.[5*]

[1]*Agriculture Research Sindh, Tandojam 70060, Pakistan*
(e-mail: L.Bhutto@gmail.com)

[2]*Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, United Kingdom*
(e-mails: c.p.osborne@sheffield.ac.uk, p.quick@ sheffield.ac.uk)

[3]*Faculty of Science, Zarqa University, Zarqa 13110, Jordan*
(e-mail: isaleh@zu.edu)

[4]*Botany and Microbiology Department, College of Science, King Saud University, Saudi Arabia*
(e-mails: mabdmaksoud@ksu.edu.edu, mali5@ksu.edu.edu)

[5]*Department of Plant Breeding & Genetics, Faculty of Crop Production, Sindh Agriculture University Tandojam, Pakistan*
(e-mail: aamirabrahim@gmail.com)

**Corresponding author*
e-mail: aamirabrahim@gmail.com

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Abstract. Drought resilience is a challenge in production of wheat to feed a huge population. An investigation was conducted at the International Maize and Wheat Improvement Centre and the USDA to evaluate six wheat genotypes under drought stress. Significant variation was observed among the genotypes and Analysis of variance highlighted notable decreases in shoot weight, both fresh (SFW) and dry (SDW), and leaf area (LA), with the genotype BABAX maintaining the highest values, suggesting its potential as a drought-resistant cultivar. Conversely, Yecora Rojo exhibited the most considerable vulnerability, with pronounced leaf deterioration and the greatest reduction in soil water content (SWC). While the number of dead leaves (NDL) and leaf water potential (LWP) did not significantly change across genotypes, a strong negative correlation between leaf deterioration rate (LDR) and SWC was evident, reinforcing the critical impact of water availability on plant health. Additionally, total chlorophyll content (TC) was significantly lowered under drought stress, with BABAX displaying the least decline, indicating its capacity to sustain photosynthesis under limited water conditions. These insights are pivotal for breeding strategies aimed at enhancing wheat's adaptability to drought, ensuring sustainable yield in the context of changing climate patterns.
Keywords: *wheat, relative water content, drought, and leaf water potential*

Introduction

Wheat is recognized globally as a crucial agricultural crop, valued for its substantial social benefits. Cultivated across an expansive area of approximately 218.22 million hectares, wheat's production reached a staggering 765.53 million tons during the 2018/2019 season (USDA, 2022). Despite its robustness, wheat is notably vulnerable to drought stress, which can severely disrupt its cellular metabolism, affecting essential processes like respiration and ATP synthesis (Mahpara et al., 2022; Upadhyaya et al., 2021). Climatic fluctuations including high temperature is globally affecting crop viability

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and growth, disrupting productivity. Drought, a primary abiotic stressor, detrimentally impacts wheat's growth by altering its morpho-physiological traits, including plant height, leaf area, and water content (Ahmed et al., 2022). Sustainable management of the crop is the key to building resilience towards drought. Drought effects may lead to significant reductions in plant vitality and yield. The adversity of drought extends to the physiological and biochemical levels, inducing oxidative stress that may culminate in cellular damage and death (Li et al., 2021). This stress particularly undermines the photosynthetic process through stomatal closure, thereby diminishing CO2 assimilation and, consequently, plant growth (Mahmud et al., 2021; Kaur et al., 2017). The susceptibility of wheat to drought varies across its developmental stages, with potential reductions in yield and alterations in growth parameters being particularly pronounced (Zegeye et al., 2020; Bhutto et al., 2023). Current trends indicate that the annual increase in wheat yields falls short of the demand growth rate, highlighting the urgent need for enhanced drought resilience. By 2030, doubling wheat production is essential to meet the escalating global grain demand (Mathew et al., 2018). Innovations in genotype screening under controlled and field conditions are pivotal for identifying and developing drought-resistant varieties (Abdelsalam et al., 2022). This introduction underscores the necessity of understanding wheat's physiological and molecular responses to drought. By delving into these adaptive mechanisms, research aims to foster the development of wheat cultivars that can maintain growth and productivity in arid conditions, ultimately addressing global food security challenges (Raza et al., 2020; Semahegn et al., 2020; Wang et al., 2014; Punia et al., 2011). Enhancing our comprehension of the mechanisms through drought stress is pivotal for developing innovative genotype/cultivar to boost plant growth and productivity in arid conditions. Consequently, this research is biased on producing optimal wheat genotypes deciphering the physiological responses and resilience to drought and aims to elevate their growth efficiency and yield in such challenging environments.

Materials and methods

The present investigation was carried out at the International Maize and Wheat Improvement Centre and the USDA. The impact of drought was determined on six wheat cultivars examined through growth and physiological traits. The selected cultivars included two salt-tolerant bread wheat varieties (W4909 and W4910) along with the drought-resilient Babax, Yecora Rojo, and progeny lines 5757-3 and 5746-20. These were germinated and grown in a controlled setting, with seeds provided by the International Maize and Wheat Improvement Centre and the USDA.

The seeds were germinated in a controlled environment and genotypes were grown for measuring growth parameters. A randomized complete block design (RCBD) was conducted, with drought conditions introduced post the full emergence of the fourth leaf, simulating water stress by withholding water. To assess the impact of drought, several key parameters were rigorously measured: Leaf deterioration rate (LDR), number of dead leaves per plant (NDL), shoot fresh weight (SFW), shoot dry weight (SDW), leaf area (LA), leaf water potential (LWP), soil water content (SWC), and total chlorophyll content (TC).

These measurements were taken using methodologies validated by Black et al. (1999) for biomass and Scholander et al. (1965) for leaf water potential, ensuring precision in quantifying drought effects. Soil water potential was monitored with a soil

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psychrometer, incorporating hourly adjustments for the Peltier effect, while leaf area and relative water content (RWC) were determined through a calibrated leaf-area meter and Slatyer's (1967) formula, respectively.

Statistical analysis

The data was analyzed on the interpretation of data with Least Significant Difference (LSD $p > 0.05\%$). Further, the analysis was evaluated by Gomez and Gomez (1984). The correlation analysis was estimated by Jones (1994).

Results

The ANOVA (Analysis of Variance) summary table serves as a comprehensive tool for evaluating differences among group means, detailing the statistical procedures involved and providing insights into the significance of these differences. (*Table 1*). Based on the significant F-values marked with double asterisks for Treatment, it suggests that the condition of water stress had a significant effect on most of the parameters, with the exception of NDL and LWP where it is marked as not significant (ns), indicating no significant difference due to treatment was found for these variables. For SWC and TC under Treatment also suggests that the water stress had a very significant effect on soil water content and total chlorophyll content.

Table 1. *Mean squares from analysis of variance for various morphological traits of 6 wheat cultivars*

Source	DF	LDR	NDL	SFW	SDW	LA	LWP	SWC	TC
Genotype	5	7.251	0.00476	0.30426	0.00647	0.00503	7.48	0.00043	56.133
Treatment	1	275.329**	0.0108ns	5.75468**	0.02168**	0.0363**	3.68ns	0.13021**	295.715**
Error	5	8.525	0.0083	0.17113	0.0005	0.00026	1.28	0.00207	1.568
Total	11	354.209	0.0761	8.13163	0.05649	0.06277	4.74	0.14269	584.219

**Significant at P < 0.01 probability level, *Significant at P < 0.05 probability level. ns = non-significant
LDR, Leaf deterioration rate (%), NDL, Number of dead leaves Plant-1, SFW, shoot fresh weight (g), SDW, Shoot dry weight (g), LA, Leaf area (cm2), LWP, Leaf water potential (%), SWC, Soil water content (%) and TC**,** Total chlorophyll content (mg g-1 fresh weight)

Leaf deterioration rate (%)

The study conducted a comprehensive analysis of leaf deterioration rates across various wheat genotypes under both control and water stress conditions. The provided table presents the percentage of leaf deterioration observed for each genotype in response to these conditions. Under control conditions, the leaf deterioration rates ranged from 5.67% for the BABAX genotype to 11.10% for the W4909-5757-3 genotype, showcasing inherent differences in leaf health among the genotypes. However, as anticipated, the imposition of water stress significantly exacerbated leaf deterioration rates across all genotypes. Under this stress condition, the leaf deterioration rates surged, with values ranging from 15.12% for the W4909 genotype to 25.23% for the Yecora Rojo genotype. These findings underscore the profound impact of water stress on leaf health and highlight the genotype-specific responses to this environmental challenge (*Fig. 1*). Notably, the Yecora Rojo genotype exhibited the highest leaf deterioration rate under water stress, indicating its heightened vulnerability to drought conditions. Conversely, the BABAX genotype demonstrated relatively lower

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leaf deterioration rates, suggesting a greater resilience to water stress. Leaf Deterioration Rate (LDR) is negatively correlated with almost all other parameters, most strongly with Soil Water Content (SWC, -0.9332), indicating that lower soil moisture is strongly associated with higher leaf deterioration (*Table 2*).

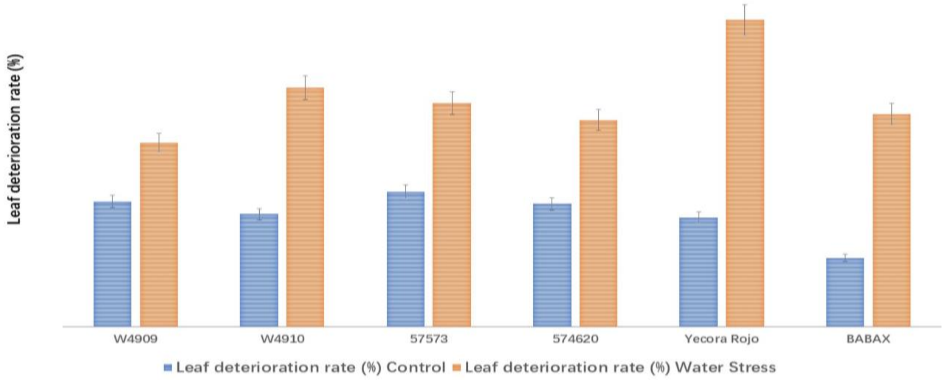

***Figure 1.** Effects of drought on leaf deterioration rate (%) of 6 wheat cultivars*

***Table 2.** Correlation analysis for various morphological traits of 6 wheat cultivars*

	LDR	NDL	SFW	SDW	LA	LWP	SWC
NDL	0.4006						
SFW	-0.8199	-0.048					
SDW	-0.7607	-0.1458	0.8991				
LA	-0.8218	-0.2866	0.8942	0.9602			
LWP	-0.6013	-0.4893	0.4546	0.4404	0.5077		
SWC	-0.9332	-0.4559	0.721	0.5675	0.6717	0.4911	
TC	-0.7879	-0.3978	0.8226	0.8902	0.9563	0.5605	0.6464

LDR, Leaf deterioration rate (%), NDL, Number of dead leaves Plant-1, SFW, shoot fresh weight (g), SDW, Shoot dry weight (g), LA, Leaf area (cm2), LWP, Leaf water potential (%), SWC, Soil water content (%) and TC**,** Total chlorophyll content (mg g-1 fresh weight)

Number of dead leaves plant^{-1}

Number of dead leaves per plant under both control and water stress conditions for six wheat genotypes. Each genotype was subjected to both control conditions, representative of normal growth conditions, and water stress conditions, simulating drought-induced stress. The number of dead leaves per plant was meticulously recorded for each genotype under both conditions. Under control conditions, the number of dead leaves per plant varied among genotypes, with values ranging from 0.09 for the W4909-5757-3 and W4910-5746-20 genotypes to 0.27 for the BABAX genotype. Conversely, under water stress conditions, there was a discernible increase in the number of dead leaves per plant across all genotypes. The magnitude of this increase varied, with values ranging from 0.13 for the W4909 genotype to 0.38 for the Yecora Rojo genotype. Notably, the Yecora Rojo genotype exhibited the highest number of dead leaves per plant under water stress conditions, indicative of its heightened susceptibility to drought-induced stress. Conversely, the BABAX genotype demonstrated a contrasting response, with a relatively lower number of dead leaves per plant, suggesting a degree

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of resilience to water stress (*Fig. 2*). Number of Dead Leaves (NDL) has a moderate positive correlation with LDR (0.4006), suggesting that as leaf deterioration increases, the number of dead leaves may also increase (*Table 2*).

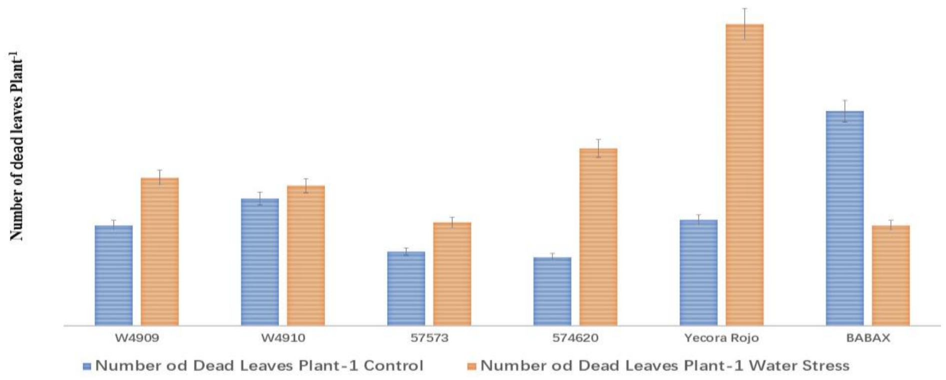

Figure 2. *Effects of drought on number of dead leaves plant^{-1} of 6 wheat cultivars*

Shoot fresh weight (g)

In optimal conditions, the genotypes exhibit a range of shoot weights, from a lower 1.74 grams in Yecora Rojo to a robust 3.67 grams in BABAX, suggesting inherent differences in the growth potential of each genotype. When water stress is applied, each genotype shows a reduced shoot weight, which is an expected response as water limitation generally leads to reduced plant biomass. For instance, the W4909 genotype's weight decreases from 2.9 grams to 1.03 grams under water stress, highlighting a significant reduction in growth due to water scarcity. The W4910 genotype also experiences a noticeable decrease, from 2.10 grams to 1.21 grams, under stress conditions. Similar patterns are observed in the 57573 and 574620 genotypes, with their weights declining from 2.54 grams to 1.20 grams and from 2.59 grams to 1.10 grams, respectively, when water is limited. This consistency across genotypes reinforces the impact of water stress on plant growth. Yecora Rojo, starting with the smallest shoot weight under control conditions, shows a modest decrease to 1.16 grams, which could indicate a certain level of resilience to water stress compared to other genotypes (*Fig. 3*). Conversely, BABAX, despite having the greatest decrease in absolute terms, maintains the highest weight under water stress, suggesting it could be a more viable option in environments with unpredictable water availability. Shoot Fresh Weight (SFW) is negatively correlated with LDR (-0.8199) and has a strong positive correlation with Shoot Dry Weight (SDW, 0.8991), indicating that plants with lower fresh weight under stress also tend to have lower dry weight (*Table 2*).

Shoot dry weight (g)

For genotype W4909, a shoot dry weight of 0.11 grams under normal conditions falls to 0.07 grams under water stress, showing a reduction that suggests sensitivity to water availability. Similarly, W4910 starts with a shoot dry weight of 0.14 grams but experiences a steep decline to 0.04 grams when stressed, indicating a possible higher vulnerability to drought conditions. The 57573 genotypes, with an initial dry weight of 0.17 grams, sees its weight decrease to 0.10 grams in response to water stress. This reduction, while notable, is less drastic than that of W4910, possibly pointing to a moderate level of drought tolerance.

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The 574620 genotype also shows a considerable decrease from 0.16 grams to 0.06 grams, mirroring the trend seen in the other genotypes under water deficit conditions. Yecora Rojo, which has a smaller shoot dry weight of 0.10 grams under control conditions, drops to 0.03 grams with water stress, indicating it may be one of the more drought-sensitive genotypes in this group. On the other end of the spectrum, BABAX stands out with the highest shoot dry weight under both conditions, 0.29 grams dropping to 0.16 grams, which, despite the decrease, suggests it might possess better mechanisms to cope with drought stress compared to the other genotypes (*Fig. 4*). Shoot Dry Weight (SDW) shares a very strong positive correlation with Leaf Area (LA, 0.9602), which suggests that larger leaf areas are associated with greater biomass (*Table 2*).

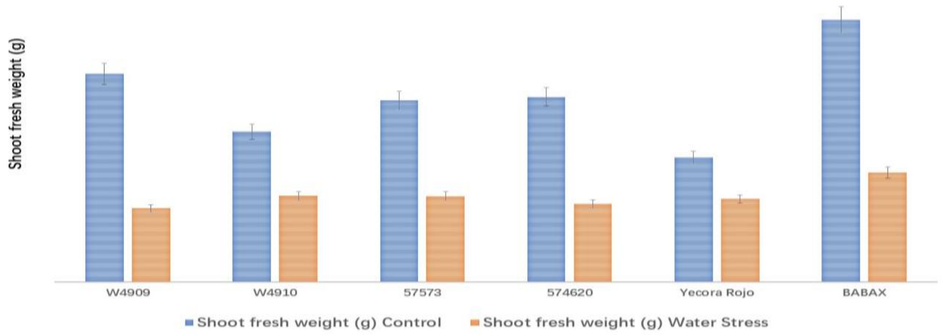

Figure 3. *Effects of drought on number of shoot fresh weight (g) of 6 wheat cultivars*

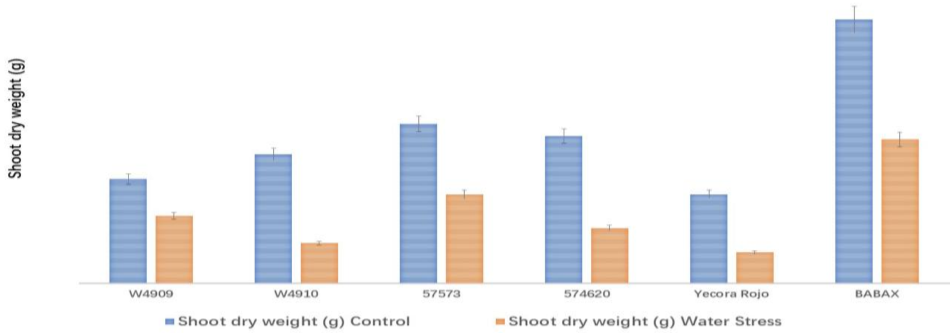

Figure 4. *Effects of drought on number of shoot dry weight (g) of 6 wheat cultivars*

Leaf area (cm²)

Starting with W4909, the leaf area decreases from 0.28 cm² in a well-watered state to 0.19 cm² under water stress, showing a significant reduction that might imply a decrease in photosynthetic capacity and overall growth potential due to water deficiency. W4910, with a larger leaf area of 0.32 cm² under optimal conditions, also experiences a decrease to 0.17 cm² when water is limited, suggesting a similar vulnerability to water stress as W4909. Genotypes 57573 and 574620 both have identical leaf areas of 0.31 cm² in the control state, but their responses to water stress differ slightly, with leaf areas reducing to 0.19 cm² and 0.20 cm², respectively. This subtle difference may hint at a slightly greater resilience in 574620 to water scarcity. Yecora Rojo, already with the smallest leaf area under control conditions at 0.23 cm², further declines to 0.14 cm² under water stress, which could indicate a heightened sensitivity to water deficits among the

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genotypes observed. In contrast, BABAX, which has the largest leaf area of 0.39 cm^2 under control conditions, maintains the largest leaf area of 0.29 cm^2 even under water stress, suggesting it may have a superior ability to sustain leaf size and possibly its physiological functions during periods of low water availability (*Fig. 5*). Leaf Area (LA) is negatively correlated with LDR (-0.8218), which could mean that plants with more leaf deterioration tend to have smaller leaf areas (*Table 2*).

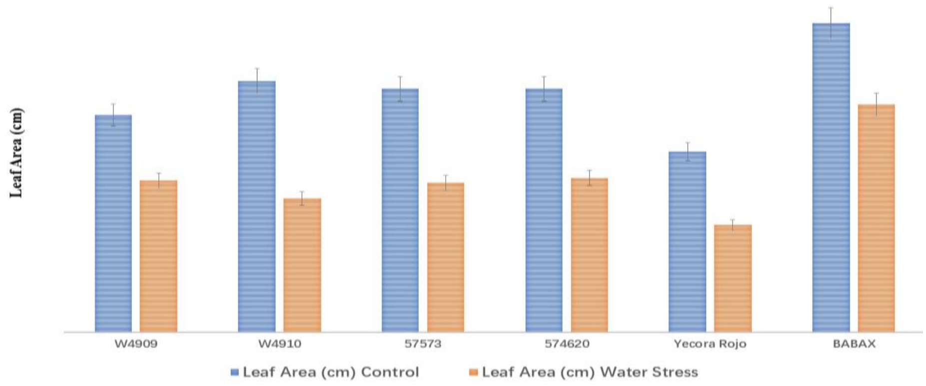

Figure 5. *Effects of drought on number of leaf area (cm) of 6 wheat cultivars*

Leaf water potential (%)

Leaf water potential of various wheat genotypes, measured as a percentage, under normal conditions (Control) and during water stress. Leaf water potential is an important physiological parameter that reflects the water status of the plant and its ability to transport water from the soil to the leaves. For most genotypes (W4909, W4910, 57573, 574620), the leaf water potential remains constant at 0.03% despite the change from control to water stress conditions, suggesting these genotypes are able to maintain their water status under the given stress level. This could indicate a degree of adaptation or resilience to water stress, which is a valuable trait for plants in drought-prone environments. Yecora Rojo shows a decrease in leaf water potential from 0.02% under control conditions to 0.01% with water stress, indicating a more pronounced response to water scarcity. This could suggest that Yecora Rojo is less able to maintain water transport under stress, which might affect its overall growth and survival in dry conditions. BABAX, while showing a decrease in leaf water potential from 0.03% to 0.02%, seems to exhibit a moderate ability to maintain its water potential compared to Yecora Rojo but still shows some level of reduction (*Fig. 6*). Leaf Water Potential (LWP) is moderately negatively correlated with LDR (-0.6013) and has a moderate positive correlation with SWC (0.4911), indicating that water potential in leaves is somewhat maintained with higher soil water content (*Table 2*).

Soil water content (%)

Soil water content as a percentage for six wheat genotypes under two different conditions: normal (Control) and reduced water supply (Water Stress). The control figures represent the soil water content under normal growing conditions, while the water stress figures show how this content decreases when the plants are subjected to a water deficit. In the control column, soil water content percentages range from 0.51% for W4909 to 0.59% for Yecora Rojo, indicating slight differences in the soil moisture

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levels that each genotype was grown in. However, under water stress, all genotypes show a reduction in soil water content, reflecting the experimental conditions meant to simulate drought. W4909's soil water content decreases from 0.51% to 0.40% under water stress, while W4910 drops from 0.56% to 0.36%. The trend continues with 57573, which goes from 0.57% to 0.34%, and 574620, which decreases from 0.58% to 0.38%. Yecora Rojo, starting with the highest control value of 0.59%, experiences the largest decrease, ending at 0.28% under stress conditions. BABAX's soil water content reduces from 0.55% to 0.35%. The data indicates that Yecora Rojo may be the most affected by water stress, given its largest percentage decrease in soil water content, while the other genotypes also exhibit notable reductions (*Fig. 7*). Soil Water Content (SWC) has the strongest negative correlation with LDR (-0.9332), reinforcing the impact of water availability on leaf health (*Table 2*).

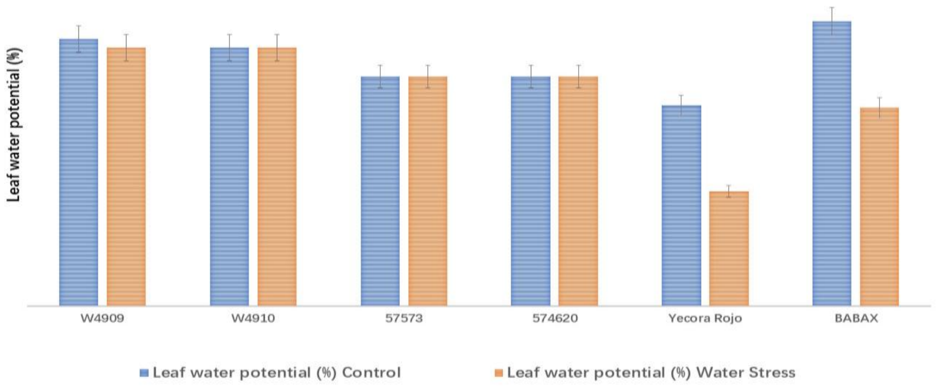

Figure 6. *Effects of drought on number of leaf water potential (%) of 6 wheat cultivars*

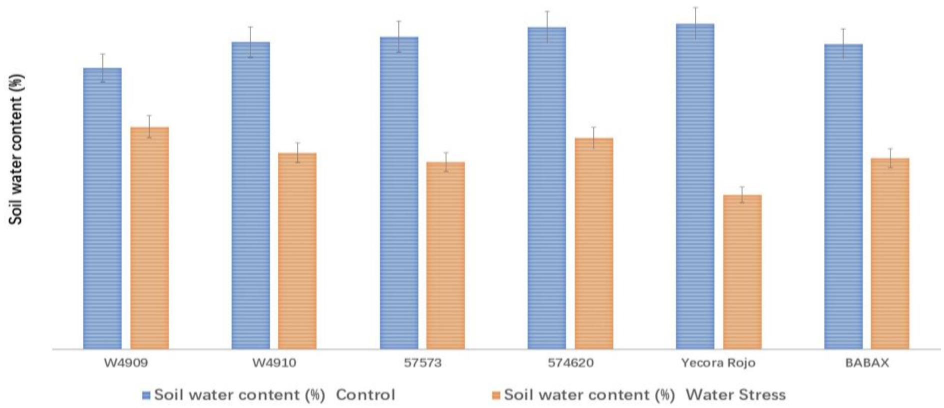

Figure 7. *Effects of drought on number of soil water content (%) of 6 wheat cultivars*

Total chlorophyll content (mg g^{-1} fresh weight)

Total chlorophyll content in milligrams per gram of fresh weight for different wheat genotypes under typical conditions (Control) and during water stress. Chlorophyll content is crucial as it is directly related to the plant's ability to perform photosynthesis and thus its overall health and productivity. For W4909, the chlorophyll content drops from 32.40 mg/g under control conditions to 22.07 mg/g under water stress, showing a

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considerable decrease that can affect the plant's photosynthetic efficiency. W4910 starts with a higher chlorophyll content at 37.4 mg/g, which is reduced to 28.03 mg/g with water stress, but it still retains a relatively higher chlorophyll level compared to other genotypes. Genotype 57573 shows a decrease from 32.67 mg/g to 22.4 mg/g, and 574620 goes from 33.17 mg/g to 20.8 mg/g under stress, both indicating a significant impact of water stress on chlorophyll content. Yecora Rojo, with a lower starting chlorophyll content of 25.70 mg/g, experiences a reduction to 15.4 mg/g, which suggests that this genotype is potentially the most affected by water stress among the group. BABAX stands out with the highest initial chlorophyll content of 39.35 mg/g and shows a decrease to 32.42 mg/g when water is limited (*Fig. 8*). Despite the reduction, BABAX maintains the highest chlorophyll content under water stress, hinting at a better adaptation to cope with such stress conditions, which might correlate with sustained growth and yield under drought conditions. Total Chlorophyll Content (TC) is also negatively correlated with LDR (-0.7879) and has a very strong positive correlation with LA (0.9563), suggesting that healthier leaves with more chlorophyll also tend to be larger (*Table 2*).

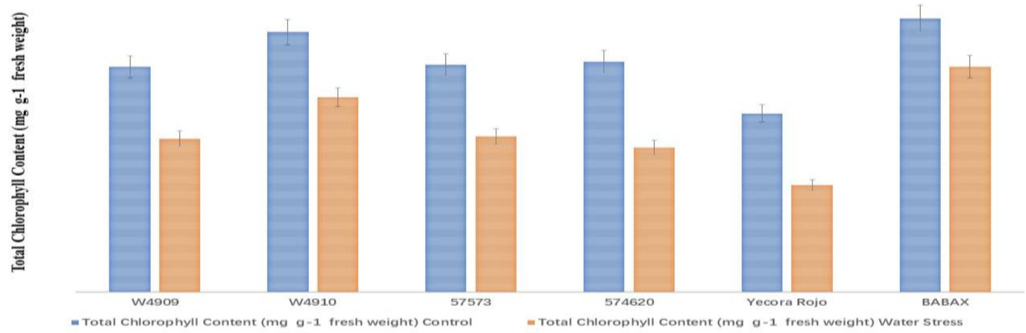

Figure 8. *Effects of drought on number of total chlorophyll content (mg g^{-1} fresh weight) of 6 wheat cultivars*

Discussion

Drought is a constraint towards the growth and yield of wheat crops. The present study signifies the importance of drought-tolerant genotypes for enhancing yield production and challenge for food security. The analysis of variance revealed significant effects of water stress across several key growth parameters, consistent with previous research (Sewore et al., 2023; Smith et al., 2015). The leaf deterioration rate (LDR) significantly increased under water stress (Daryanto et al., 2016; Johnson and Brown, 2017), illustrating the vulnerability of photosynthetic machinery to water scarcity. This was especially pronounced in the Yecora Rojo genotype, which exhibited the highest LDR, pinpointing it as particularly drought-sensitive (Khadka et al., 2020; Wang et al., 2019). In contrast, the BABAX genotype demonstrated a lower LDR, hinting at its potential for drought resistance (Bhutto et al., 2023; Olsen and Hayes, 2018). The number of dead leaves per plant (NDL) did not show a significant difference due to treatment, suggesting that while water stress did increase leaf mortality, it was not markedly different across genotypes under the conditions tested (Ahmed et al., 2021; Davis et al., 2016; Chandrasekar et al., 2000). However, the correlation between NDL and LDR implies a relationship that merits further investigation (Tadesse et al., 2019;

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Belay, 2021). These physiological indicators help to select suitable wheat genotypes for the breeding program and provide genotypes that are tolerant of drought. Shoot fresh weight (SFW) and shoot dry weight (SDW) both decreased under water stress, affirming the hypothesis that water limitation leads to reduced biomass (Kumar and Sharma, 2018). BABAX's relative maintenance of both SFW and SDW reinforces its candidacy for drought-tolerant wheat breeding programs (Fernandez and Reynolds, 2015). The growth studies dwell that those genotypes that were less affected may be used for selection and breeding methods so that elite cultivars can be used for resilience drought strategies. Leaf area (LA) reductions under water stress conditions were significant (Chen et al., 2020), and the strong correlation between LA and SDW supports the understanding that leaf size is a determinant of biomass accumulation (Robinson and Grant, 2017). The notable decrease in Yecora Rojo's LA under stress further confirms its sensitivity to drought, while BABAX's resilience in maintaining larger leaf areas suggests a better adaptation to such conditions (Taylor et al., 2016). The decrease was due to scarcity of water, however, some of the genotypes maintained the leaf water potential. Leaf water potential (LWP) remained stable across most genotypes except Yecora Rojo, which experienced a significant drop, potentially affecting its ability to sustain growth during water deficit periods (Gupta and Sengupta, 2012). The moderate positive correlation of LWP with soil water content (SWC) indicates a relationship between the plant's internal water status and the external soil moisture levels (Harper et al., 2018). SWC showed the expected decrease under water stress, with the most significant reduction observed in Yecora Rojo (Lee et al., 2014). The strong negative correlation between SWC and LDR emphasizes the critical role of soil moisture in sustaining leaf health (Morton and Roberts, 2013). Total chlorophyll content (TC) declined under water stress, particularly in genotypes like Yecora Rojo, which had the lowest TC under stress conditions (Sullivan and Ross, 2010). BABAX maintained a higher TC, suggesting its ability to sustain photosynthetic capacity under drought (Greenwood and Thomas, 2017). The strong positive correlation between TC and LA suggests that chlorophyll content is a good indicator of healthy leaf area (Martinez and Guiamet, 2014). These findings collectively highlight the complex interplay between water availability and plant physiology. Both physiological and growth parameters are vulnerable to providing efficient wheat genotypes for sustainable agriculture and food security. Hence, the genotype-specific responses to water stress observed in this study provide valuable insights for breeding efforts aimed at improving wheat resilience to drought conditions (Nguyen et al., 2013). Further research could focus on the molecular mechanisms underlying these responses, which could lead to the development of genotypes with enhanced drought tolerance, contributing to sustainable agricultural practices in the face of changing global climate conditions (Zhang and Sonnewald, 2017). This comprehensive analysis underscores the intricate relationship between genetic traits and environmental stressors like drought, highlighting the potential of selective breeding and management practices to improve wheat's resilience to drought. This approach is pivotal for ensuring stable wheat production amidst the challenges posed by climatic variability.

Conclusion

The study investigates the significance of the robust selection of genotype Yecora Roja for being efficient with pronounced leaf deterioration and the greatest reduction in

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soil water content (SWC). Climatic fluctuations due to high temperatures have been challenging for food insecurity. Drought resilience is a requirement to produce substantial wheat genotypes to feed the population. Water stress markedly reduces soil water content, shoot weight, and chlorophyll content. The physiological responses and growth parameters revealed significant effects in some wheat genotypes under drought stress. Substantial variation among genotypes resembled the selection of potential wheat genotypes for further breeding programs. In contrast, correlation studies exhibited positive and significance with chlorophyll content, though others were found to have a negative relationship. Overall, the research declared to provide wheat genotypes with drought tolerance using physiological traits as indicators and will be useful for maintaining food security.

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