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Evaluating the Performance of Wheat Germplasm under Drought Using Morphological and Physiological Traits

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Authors' Contribution
HN: Performed the research, Data curation; writing. **JK:** Investigation; assist in research and methodology; analysis; writing, review and editing. **ZUM:** Investigation, methodology and editing. **SRA:** writing; review and editing. **ARR:** review and editing. **MAK:** Review and editing. **NS:** Facilitation in research, review and editing. **NK:** review and editing. **GR:** Review and editing. **MNI:** review and editing. **BK:** Assist in research.

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ABSTRACT

This study assessed the morphological and physiological responses of multiple genotypes under drought stress to identify key traits associated with drought tolerance and yield stability. A field experiment was conducted under controlled drought conditions, and data for 16 traits, including plant height, spikelet number, tiller count, grain yield, relative water content (RWC), chlorophyll content indices (NDVI), canopy temperature (CT), and harvest index (HI) were recorded. Analysis of variance (ANOVA) revealed significant genetic variation among genotypes for most traits. Mean comparisons with two standard checks, AZRI-96 and Local White (LW), identified superior lines such as BARDC-WW-5, BARDC-WW-9, and BARDC-WW-18, which exhibited enhanced grain yield, relative water content, and physiological resilience under drought stress. Pearson correlation analysis showed strong positive associations between RWC, NDVI, grain yield, and total dry matter, while canopy temperature was negatively correlated with these traits, indicating its potential as a stress indicator. Principal Component Analysis (PCA) reduced data dimensionality, with the first two components explaining 42.7% of variation and highlighting clusters of yield-related and physiological traits. The grouping of grain yield, harvest index, RWC, and total dry matter emphasizes their critical role in drought tolerance. These findings provide valuable insights into trait interactions under drought stress and offer reliable markers for breeding drought-resilient cultivars with improved productivity in water-limited environments.

INTRODUCTION

Wheat (*Triticum aestivum* L.) belongs to family poaceae and serves as the primary source of food worldwide (Kumar et al., 2013; Nawaz et al., 2013). Wheat grains are high in fat, protein, dietary fiber, and minerals, including vitamin B complex (Shewry & Hey, 2015). Wheat is the most important food crop for one-third of the world's population because it contributes more calories and proteins to the human diet than any other cereal crop (Shewry, 2009). Wheat consumption averages approximately 318 grams per person per day, representing about 83% of total grain intake. Globally, wheat ranks second only to rice among cereal crops in terms of importance and consumption (Falola et al., 2017; Iqbal et al., 2022; Ma et al., 2023). Agronomically, wheat is recognized for its broad adaptability, being cultivated across most regions of the world, with optimal yields typically achieved in temperate climates (Ortiz et al., 2008). Asia dominates global wheat production, contributing around 44% of the total output, followed by Europe and the Americas, which account for 34% and 15%, respectively (Streit et al., 2013). Historically, the United States, France, China, India, and Russia have collectively produced approximately 53% of the world's wheat. Notably, these countries have maintained a leading role in global wheat production since the 1960s. Currently, China and India are the top two wheat-producing nations, although production trends in other countries are also evolving (Igrejas & Branlard, 2020).

Population growth and climate change are raising serious concerns about global wheat consumption and food security. By 2050, an additional 132 million tons of wheat-based food items will be required annually to meet the projected global demand. Factors such as globalization, rapid urbanization, and rising economic prosperity are driving significant dietary shifts, particularly in Asia, where the consumption of wheat-based products is rising (Pingali, 2007). To meet the demands of a growing population by the end of this century, wheat production must increase substantially (Tilman et al., 2011). However, the current rate of wheat yield growth is only 0.9% per year, which falls short of the 1.5% annual growth needed to achieve the projected 60% increase in global supply by 2050. In Pakistan, the province of Balochistan remains heavily dependent on wheat supplies from Sindh and Punjab due to limited local production. Expanding wheat cultivation in Balochistan (Pakistan's largest province by area), could significantly enhance national wheat output. The province spans approximately 34.719 million hectares, of which only 1.989 million hectares are currently under agriculture. An additional 4.826 million hectares are classified as cultivable wasteland, offering substantial potential for agricultural expansion (Ahmad et al., 2023).

However, wheat growth and development are severely affected by several biotic and abiotic stresses among which drought is most critical. Drought, in particular, has emerged as the most significant constraint under the current climate change scenario (Farooq et al., 2014; Khan et al., 2013). Climate change has intensified drought frequency and severity, leading to unpredictable and extreme weather patterns (Senapati et al., 2019). Drought stress can cause a substantial reduction in wheat yield ranging from 50% to 60%, posing a major threat to global food and nutritional security (Zhou et al., 2020). Wheat is especially sensitive to drought during key developmental stages, including tillering, jointing, booting, anthesis, and grain filling, with potential yield losses reaching up to 69% (Khan et al., 2024). Morphological traits such as seed germination, seedling vigor, leaf area, total dry weight, root-to-shoot ratio, plant height, number of tillers per plant, spike density per square meter, spikelet number per spike, spike length, days to booting, heading, anthesis, and maturity are all negatively impacted by drought stress (Taheri et al., 2011; Vahamidis et al., 2019). Moreover, drought reduces seedling vigor by disrupting water uptake, inducing oxidative stress, impairing root and shoot development, and hindering nutrient absorption (Ahmad et al., 2018). Physiologically, drought stress limits photosynthesis, inhibits cell division and expansion, alters nutrient assimilation, accelerates senescence, and disrupts hormonal balance, ultimately compromising plant productivity. Physiological traits play a vital role in varietal development and serve as effective indirect selection criteria during the advancement of breeding populations. Traits such as normalized difference vegetation index (NDVI), relative water content (RWC), and canopy temperature (CT) are particularly valuable under drought stress conditions (Ahmed et al., 2023; Karimpour, 2019). Among these, RWC is a key indicator of a plant's water status, reflecting the balance between transpiration rate and water availability in leaf tissues (Feng et al., 2009). Maintaining higher RWC under drought stress indicates better cellular hydration and stress tolerance. Osmotic adjustment, which contributes to the maintenance of cell turgor, further supports plant growth and cell expansion under water-deficit conditions, enhancing overall drought resilience.

Therefore, the primary objective of this study was to evaluate the morphological, physiological, and yield-related performance of 30 winter wheat genotypes under drought stress conditions in the semi-arid region of Balochistan. The study aimed to identify drought-tolerant genotypes based on key selection indices such as canopy temperature, relative water content (RWC), normalized difference vegetation index (NDVI), and yield components, thereby contributing to the development of climate-resilient wheat varieties for water-limited environments.

MATERIALS AND METHODS

The current experiment was conducted at Balochistan Agricultural Research and Development Center (BARDC), Quetta, during the 2022-2023 cropping season to evaluate the performance of 30 winter wheat accessions under drought stress conditions. Two check varieties, AZRI-96 and Local White were included for comparative analysis. The experimental site is situated in a semi-arid region characterized by cold winter and moderate summer. The soil type was sandy loam with gravel content and exhibited lower water holding capacity.

Experimental Design and Field Management

The experiment was laid out in a Randomized Complete Block Design (RCBD) with two replications. Each plot measured 3 m^2 (3 meters in length and 1 meter in width), with a row-to-row spacing of 20 cm. Seeds were sown at a rate of 100 kg ha^{-1}, with 30 grams of seed used per plot. Prior to sowing, uniform agronomic practices were applied across all plots, including standard irrigation (until drought stress initiation) and fertilizer application based on local recommendations.

Data Collection and Measured Traits

Agronomic, physiological, and yield-related traits were recorded using standard procedures.

Spike Length and Spikelets per Spike

Three plants per plot were randomly selected to measure spike length (excluding awns) using a ruler from the base to the tip of the spike. The number of spikelets per spike was also counted from these plants.

Plant Height

Plant height was measured from the base of the plant to the tip of the spike (excluding awns) from three randomly selected plants per genotype.

Days to Heading

Recorded as the number of days from sowing to the date when 50% of the spikes emerged from the flag leaf.

Total Dry Matter (TDM)

Biomass was harvested from the entire plot at maturity, dried, and weighed using an electronic balance. The resulted data was then converted to TDM ha^{-1}.

Grain Yield kg ha^{-1}

After threshing the harvested biomass, grain yield was recorded for each plot. The resulted grain from measured area were then converted to GY ha^{-1}.

Thousand Grain Weight (TGW)

A sample of 1000 grains from each genotype was weighed using a precision balance to determine TGW in grams.

Harvest Index (HI)

Calculated as the ratio of grain yield to total dry matter.

Physiological Parameters

Relative Water Content (RWC)

Flag leaf samples from five plants per plot were collected, placed immediately in pre-weighed plastic bottles, and transported to the laboratory. Fresh weight (FW) was recorded, followed by immersion in distilled water for 24 hours to obtain turgid weight (TW). After drying at 70°C for 48 hours, dry weight (DW) was recorded. RWC was calculated using the formula:

$$RWC(\%) = \frac{FW - DW}{TW - DW} \times 100$$

Canopy Temperature (CT)

CT was recorded using a handheld infrared thermometer to assess the genotypic response to drought stress, particularly in relation to stomatal conductance and transpiration cooling. Measurements were taken between 12:00 PM and 2:00 PM during clear, low-wind conditions to ensure consistency and capture peak thermal readings from the crop canopy. CT data were collected from the anthesis stage through to physiological maturity. Genotypes exhibiting lower canopy temperatures under stress were considered to have superior stomatal regulation and drought tolerance due to their ability to maintain cooler canopies.

Normalized Difference Vegetation Index (NDVI)

Normalized Difference Vegetation Index (NDVI) was measured using a handheld GreenSeeker device (Trimble, USA) to evaluate the photosynthetic activity, biomass accumulation, and general health of the wheat genotypes under drought conditions. NDVI readings were taken at anthesis (NDVI-1), mid-grain filling (NDVI-2), and late grain filling (NDVI-3). This index provided a non-destructive assessment of canopy vigor and was instrumental in identifying drought-affected areas and differentiating genotypes based on their ability to maintain green leaf area and productivity under water-limited conditions.

Statistical Analysis

The collected data were analyzed using STATISTIX 8.1 and JAMOVI software. Analysis of variance (ANOVA) (including both simple ANOVA and Repeated Measurement ANOVA) was conducted to determine the significance of differences among genotypes and treatments. Where significant differences were observed, the Least Significant Difference (LSD) test was applied at a 5% probability level to compare treatment means. Principal Component Analysis (PCA) was performed to identify patterns of trait variation and to reduce dimensionality for better visualization of genotype performance under drought stress. Pearson correlation analysis was also conducted to evaluate the relationships among agronomic, physiological, and yield-related traits.

RESULTS AND DISCUSSION

Analysis of variance (ANOVA) revealed significant differences among the 30 winter wheat genotypes for several morphological, physiological, and yield-related traits under drought stress conditions, indicating considerable genetic variability suitable for selection and breeding purposes. Days to heading (DTH) showed highly significant differences, indicating diverse phenological responses among genotypes. Plant height (PH) also varied significantly ($p = 0.0162$), suggesting differences in growth habit. Grain yield per hectare (GY ha^{-1}) and harvest index (HI) were significantly different ($p = 0.0242$ and $p = 0.0019$, respectively), highlighting the potential of certain genotypes for improved yield performance and efficient biomass partitioning under drought. RWC showed significant variation at RWC-2 ($p = 0.0402$) and was marginally significant at RWC-1 ($p = 0.0538$), reflecting differences in water retention capacity. NDVI at anthesis ($p = 0.0012$) and mid-grain filling ($p = 0.0407$) exhibited significant genotypic variation, indicating differences in canopy vigor and health under stress, while NDVI at the late grain filling stage ($p = 0.0726$) was marginally non-significant. In contrast, traits such as spike length, number of spikelets per spike, number of tillers per plant, total dry matter (TDM ha^{-1}), thousand kernel weight (TKW), and canopy temperature (CT-1 and CT-2) did not show significant variation, suggesting a more uniform response across genotypes for these traits under drought conditions. (Table 1).

Table 1

Analysis of Variance (ANOVA) for different tested traits under drought conditions

Source	DF	SS	MS	F	P
DTH 50%	29	2286.48	78.844	80.27	0.0000***
PH (cm)	29	1807.22	62.317	4.06	0.0162*
Spike length	29	48.331	1.666	0.90	0.6162Ns
Spike-lets	29	68.187	2.3512	1.51	0.137Ns
Tiller	29	96290	3320.4	1.22	0.2950Ns
GY ha^{-1}	29	2.215E+07	763630	2.11	0.0242*
TDM ha^{-1}	29	2.334E+08	8049455	1.49	0.1423Ns
HI %	29	1299.79	44.8204	3.05	0.0019**
TKW (g)	29	357.87	12.340	1.03	0.4770Ns
RWC-1	29	1636.89	56.444	1.84	0.0538*
RWC-2	29	1818.05	62.691	1.94	0.0402*
CT-1	29	68.457	2.3606	1.08	0.4157Ns
CT-2	29	93.068	3.2092	1.19	0.3170Ns
NDVI-A	29	2727.48	94.0511	3.23	0.0012**
NDVI-MGF	29	2068.73	71.3356	1.93	0.0407*
NDVI-LGF	29	2210.00	76.206	1.73	0.0726

The present study aimed to evaluate wheat genotypes for their morphological and physiological responses under drought stress conditions to identify drought-resilient candidates for breeding programs. Significant variability was observed among the tested genotypes for most of the traits studied, reflecting the genetic potential of these lines to perform under limited water availability. A detailed comparison with the two standard checks, AZRI-96 and Local White (LW), helped to benchmark performance. AZRI-96, a known drought-tolerant genotype, exhibited moderate plant height (80 cm), a relatively short spike length (8.49 cm), and produced a respectable grain yield of 2437 kg ha^{-1}. It also maintained a high RWC of 82.9%, a crucial physiological trait linked with cellular hydration and turgor maintenance under stress. In contrast, LW, though the tallest genotype (95 cm) with longer spikes (10.9 cm), yielded significantly less (1783 kg ha^{-1}), likely due to a lower TDM kg ha^{-1} and physiological inefficiency in water use, as reflected by its RWC (76.2%) and slightly lower NDVI (54.8) (Table 2).

Among the test entries, several genotypes outperformed these checks across morphological and physiological traits. BARDC-WW-5 stood out as the top performer, registering the highest grain yield (3173 kg/ha), high TDM ha^{-1} (11817 kg ha^{-1}), and favorable RWC (82.3%). Its harvest index (27.1) indicated efficient partitioning of biomass towards grain production, a key trait under drought stress (Keyvan, 2010; Shahi et al., 2025). Additionally, its higher NDVI (56.5) and lower canopy temperature (23.7 °C) suggest a sustained photosynthetic capacity and better evaporative cooling under stress, critical features for maintaining productivity in arid environments (Anwaar et al., 2020). BARDC-WW-13 also showed strong performance, producing 2927 kg/ha grain yield, the highest TDM ha^{-1} (14307 kg ha^{-1}), and good physiological resilience (RWC 79.0%, NDVI 57.2%). The superior dry matter accumulation indicates a robust vegetative growth phase, while a harvest index of 20.4 shows its effective conversion into reproductive output (Chowdhury et al., 2021). Similarly, BARDC-WW-3 displayed high spikelet number (18.4), elevated RWC (83.1%), and a solid harvest index (26.6), pointing to its strong reproductive potential and physiological drought tolerance (Geravandi et al., 2011) (Figure 1). Physiologically, the RWC and NDVI are strong indicators of genotypic adaptability to drought stress, as higher values are associated with better osmotic adjustment and sustained leaf function under water scarcity (Shahi et al., 2022; Thapa et al., 2019). For instance, BARDC-WW-18 (RWC 80.2%, NDVI 57.3%) and BARDC-WW-20 (RWC 79.7%, NDVI 54.0%) maintained excellent physiological status, contributing to higher grain yields of 2890 and 2110 kg ha^{-1}, respectively. Their performance also indicates that these genotypes managed to avoid excessive transpiration loss, as evidenced by relatively lower canopy temperatures (24.9 and 24.4 °C) (Chowdhury et al., 2021).

Conversely, some genotypes such as BARDC-WW-12 and BARDC-WW-24 showed poor adaptation to drought, yielding only 440 and 950 kg ha^{-1} respectively. Despite moderate RWC values, their low TDM ha^{-1} and harvest indices suggest inefficiency in biomass accumulation and distribution to grain under water-limited conditions (Geravandi et al., 2011). Genotypes such as BARDC-WW-22 and BARDC-WW-11 also demonstrated poor harvest indices (13.5 and 14.0), indicating that despite some vegetative robustness, they failed to translate growth into reproductive success under drought stress (Shahi et al., 2024). The integration of both morphological traits (plant height, spike length, spikelets, tillers, yield components) and physiological indicators (RWC, NDVI, canopy temperature) provided a comprehensive understanding of genotypic behavior under drought (Figure 2 and Figure 3). Genotypes such as BARDC-WW-5, BARDC-WW-13, BARDC-WW-3, and BARDC-WW-18 emerged as promising drought-tolerant lines combining desirable morphological traits and physiological adaptability. These lines warrant further multi-location evaluation and molecular characterization for inclusion in breeding programs targeting climate-resilient wheat varieties.

Figure 1

Relative Water Content % for RWC-1, RWC-2 and Average of different tested genotypes

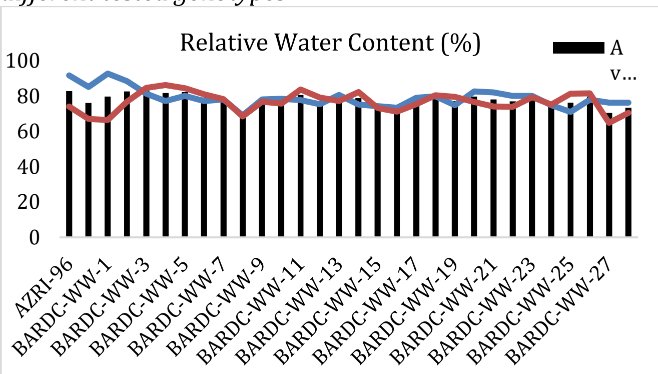


Figure 2

Canopy temperature recorded after anthesis as CT-1 and CT-2 for different tested genotypes

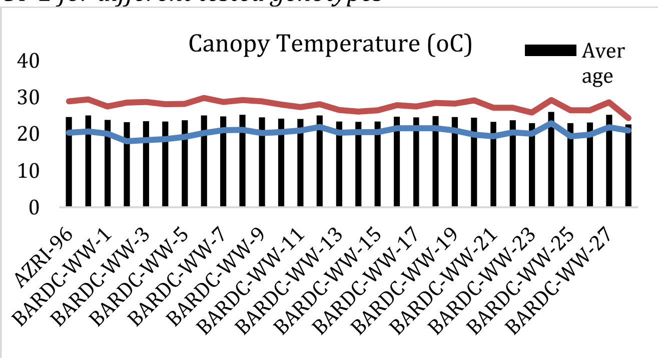


Figure 3

NDVI measurements at anthesis, mid grain filling and late grain filling along with repeated measurements

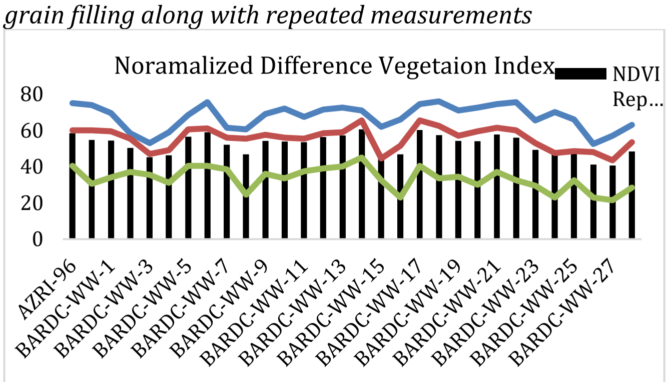


Table 2

Mean comparison of morphological and physiological traits for different winter wheat under drought stress conditions

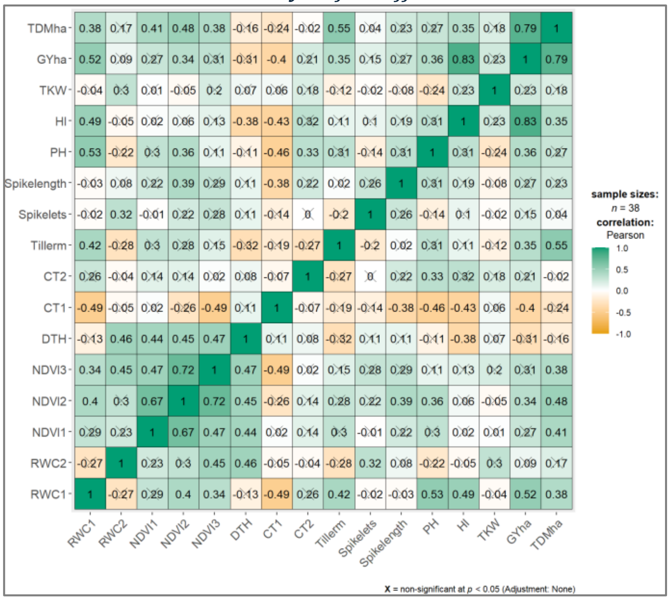
Genotype	PH	SL	S-lets	Tiller	GY ha^{-1}	TDM ha^{-1}	HI%	TKW	RWC	NDVI	CT
AZRI-96	80	8.49	17.7	271	2437	12023	208	26.9	82.9	58.5	24.6

LW	95	10.90	16.7	222	1783	9523	1902	27.2	76.2	54.8	25
BARDC-WW-1	84.5	10.6	16.6	221	2437	9460	25.7	29.1	79.7	54.3	23.8
BARDC-WW-2	85	109	17.1	164	2010	8877	22.5	24.3	82.7	50.3	23.2
BARDC-WW-3	83.5	11.5	18.4	112	1467	5730	26.6	24.9	83.1	45.2	23.5
BARDC-WW-4	79.5	9.5	17.1	136	2083	9057	23.1	34.5	81.8	46.3	23.4
BARDC-WW-5	83.5	10.9	17.3	182	3173	11817	27.1	26.8	82.3	56.5	23.7
BARDC-WW-6	84	10.9	16.4	165	2080	9870	21.0	31.4	79.2	59.0	25
BARDC-WW-7	80.5	9.2	17.2	143	1793	9713	18.4	26.3	78.2	52.0	24.8
BARDC-WW-8	74.5	9.5	15.2	181	1837	9133	19.4	30.8	68.8	46.8	25.2
BARDC-WW-9	76.5	10.8	18.6	196	2630	11297	23.8	30.6	77.5	54.2	24.5
BARDC-WW-10	78	11.1	16.2	179	2513	11463	21.9	29.6	77.2	53.8	24.2
BARDC-WW-11	66.5	10.3	17.4	132	1400	9393	14.0	29.8	80.7	53.5	24.1
BARDC-WW-12	70.5	8.5	17.2	113	440	6493	6.78	29.1	77.3	56.3	25
BARDC-WW-13	74	10.1	17.1	267	2927	14307	20.4	27.4	79.0	57.2	23.4
BARDC-WW-14	75.5	11.2	18.1	159	990	8363	11.3	24	78.8	60.5	23.3
BARDC-WW-15	68.5	9.9	16.1	137	1533	7367	21.7	27.9	73.7	46.3	23.4
BARDC-WW-16	68.5	10.1	16.4	220	1583	8650	18.2	29.2	72.4	46.8	24.7
BARDC-WW-17	74.5	10.5	15.8	185	1253	8720	13.9	26.5	77.3	60.2	24.5
BARDC-WW-18	81	10.6	19.1	123	2890	11233	25.6	27.7	80.2	57.3	24.9
BARDC-WW-19	67.5	10	17.3	172	1790	7903	22.6	29.4	77.3	54.2	24.6
BARDC-WW-20	79	10.5	17.1	163	2110	10753	18.5	25.8	79.7	54.0	24.4
BARDC-WW-21	74.5	10.9	17.4	170	1897	10290	18.4	27.6	78.1	57.7	23.3
BARDC-WW-22	91	11.1	15.1	198	1493	10813	13.5	32.4	77.1	56.0	23.7
BARDC-WW-23	86.5	9.6	15.3	184	1587	8123	19.4	27.5	79.7	49.3	22.9
BARDC-WW-24	68.5	10.2	16.2	147	950	5197	18.2	25.1	75.1	46.8	26
BARDC-WW-25	68	9.7	16.2	142	1583	6480	24.1	26.1	76.3	49.0	22.9
BARDC-WW-26	71.5	7.9	17.1	207	1683	7490	21.2	28.9	79.7	41.2	23.1
BARDC-WW-27	72	8.9	19.4	175	1803	7990	21.2	23.8	70.6	40.7	25.2
BARDC-WW-28	67.5	9.2	18.5	231	1203	8653	13.2	24.5	73.5	48.3	22.6

Pearson correlation analysis was conducted to examine the interrelationships among morphological and physiological traits under drought conditions (Mwadzingeni et al., 2016). The results revealed several significant correlations that provide insights into the mechanisms of drought tolerance. RWC measured at the first stage (RWC1) showed a strong and significant positive correlation with NDVI-MGF, NDVI-LGF, PH, HI, GY ha^{-1}, and TDM ha^{-1}. This suggests that higher relative water content during early drought stress enhances photosynthetic activity (as reflected by NDVI), biomass accumulation, and ultimately grain yield (Wasaya et al., 2021). In contrast, RWC1 showed a strong negative correlation with canopy temperature at the first stage (CT1), indicating that genotypes maintaining higher tissue hydration under drought exhibit cooler canopies, an indicator of better stomatal regulation and transpiration efficiency (Thakur et al., 2022). RWC measured at the second stage (RWC2) also displayed a strong positive correlation with late-grain filling, DTH, and number of spikelets per spike. This indicates that sustained hydration during later growth stages supports prolonged vegetative growth and enhanced reproductive development, which are critical for yield formation under water-limited conditions. NDVI measurements (A-anthesis, MGF-mid-grain filling stage and LGF-late grain filling stage) were strongly positively correlated with each other, highlighting the consistency of chlorophyll content and canopy vigor across growth stages (Figure 1). Moreover, NDVI values were significantly and positively correlated with GY ha^{-1} and TDM ha^{-1}, demonstrating that genotypes with healthier canopies and higher chlorophyll content tend to accumulate more biomass and produce higher yields. NDVI-LGF exhibited a strong negative correlation with CT1, reinforcing that genotypes with higher photosynthetic capacity maintain lower canopy temperatures under drought stress, a key adaptive trait for heat and water stress resilience (Jokar et al., 2018). DTH was positively correlated with RWC2, NDVI-A, NDVI-MGF, and NDVI-LGF, suggesting that genotypes maintaining better hydration and canopy greenness tend to have delayed heading (figure 1). While this may confer a longer vegetative period for biomass accumulation, it was negatively correlated with HI, implying that a delay in heading might not always translate into efficient grain partitioning under drought stress (Anwaar et al., 2020). CT1 showed a strong negative correlation with RWC1, NDVI-LGF, spike length, PH, HI, and GY ha^{-1}. This indicates that genotypes with higher water content and better canopy health tend to have cooler canopies, longer spikes, greater plant height, and superior yield performance, traits desirable under drought stress (Ren et al., 2019). High canopy temperature is typically associated with reduced stomatal conductance and compromised photosynthesis, which negatively impacts yield-related traits. The number of tillers per meter was positively correlated with RWC1, GY ha-1, and TDM ha^{-1}, indicating that genotypes capable of maintaining better water status tend to produce more tillers, contributing to increased biomass and grain production. PH, HI, GY ha^{-1}, and TDM ha^{-1} all showed a strong positive correlation with RWC1, underlining the importance of water retention capacity in determining overall growth and productivity under drought conditions. Additionally, PH, GY ha^{-1}, and TDM ha^{-1} were positively correlated with NDVI-MGF, further supporting the link between canopy health and yield (Figure 4). A particularly strong positive correlation was observed between TDM ha^{-1} and GY ha^{-1}, emphasizing that higher biomass production under drought conditions often translates into increased grain yield, especially when accompanied by an efficient harvest index (Assefa et al., 2017).

Figure 4

Pearson's correlation analysis for different tested traits



Principal Component Analysis (PCA), developed by Pearson in 1901, is a dimensionality reduction method widely used in agricultural research to condense large datasets into meaningful components (Rymuza et al., 2012). PCA was performed to assess the contribution of different variables to the principal components, aiding in the identification of key features and grouping associated traits to enhance germplasm breeding. In this study, 16 traits were analyzed using PCA. The first two principal components (PC1 and PC2) accounted for 26.4% and 16.3% of the total variation, respectively, cumulatively explaining 42.7% of the variability (Figure 2). Five out of sixteen principal components had eigenvalues greater than 1, collectively contributing to 75.5% of the total cumulative variation, with eigenvalues of 4.56, 2.80, 1.81, 1.56, and 1.31, respectively (Table 3). The scree plot further confirmed the significance of the first five components, as they were positioned above the eigenvalue threshold of 1. Component loadings were examined to assess patterns and relationships between variables, with loadings interpreted as correlation coefficients. A cutoff value of 0.3 was applied to determine significant contributions. PC1 was primarily influenced by GY ha^{-1}, RWC1, HI, and TDM ha^{-1}, whereas PC2 was dominated by RWC2, mid-grain filling, late-grain filling, and DTH (Table 3). The PCA biplot revealed clustering patterns, with GY ha^{-1}, TDM ha^{-1}, RWC, HI, Tiller-m, and TKW grouping together, indicating strong correlations among these traits. In contrast, DTH was positioned in the opposite direction. Additionally, NDVI-A, NDVI-MGF, NDVI-LGF, and spike length formed a separate cluster, suggesting a distinct relationship among these variables (Muhammad et al., 2025). Moreover, the PCA analysis further supported the results from the correlation analysis by showing the clustering of traits such as NDVI-A, NDVI-MGF, NDVI-LGF, spikeletes and spike length suggesting a strong positive correlation with each other (Figure 5). While on the other hand DTH, RWC2 and HI moving in opposite direction at PCA biplot indicating a negative correlation with each other.

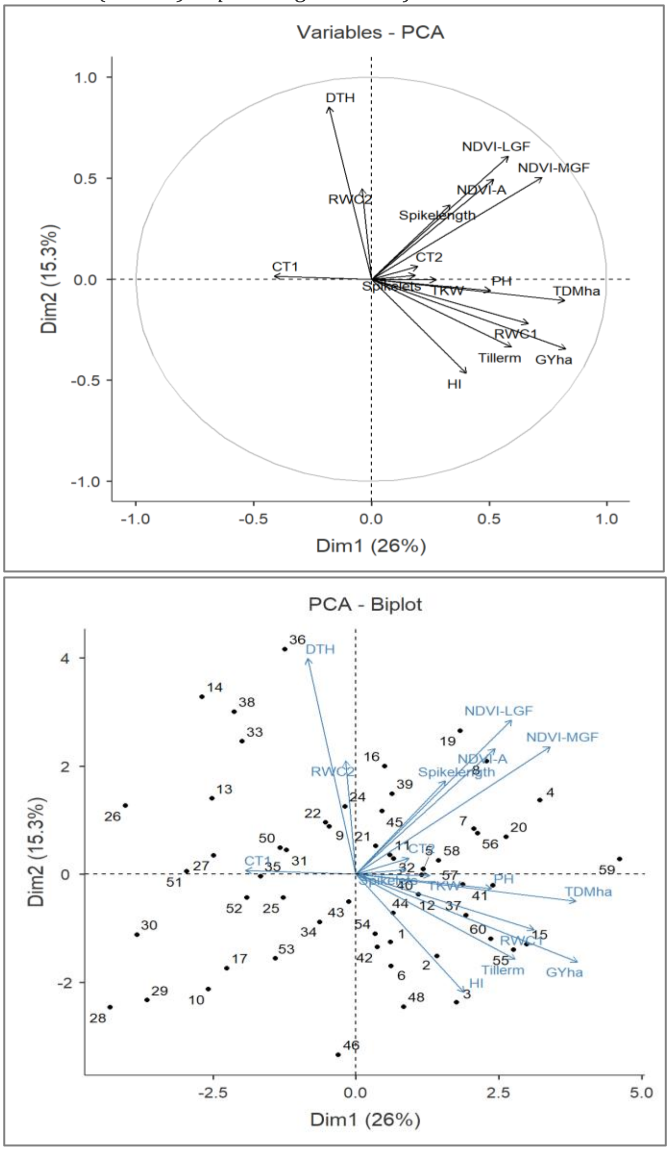
Table 3

Eigenvalues, percentage of variance explained, and cumulative variance for the first five principal components derived from the analysis of 16 agronomic traits.

Component	Eigenvalue	% of Variance	Cumulative %
1	3.9650	26.4336	26.4
2	2.4428	16.2853	42.7
3	1.9081	12.7206	55.4
4	1.3660	9.1066	64.5
5	1.2405	8.2700	72.8
6	1.0289	6.8594	79.7
7	0.7844	5.2290	84.9
8	0.6176	4.1171	89.0
9	0.3823	2.5485	91.6
10	0.3456	2.3042	93.9
11	0.3069	2.0458	95.9
12	0.2810	1.8731	97.8
13	0.1763	1.1755	99.0
14	0.1443	0.9621	99.9
15	0.0104	0.0692	100.0

Figure 5

PCA biplot showing trait relationships, with PC1 (26.4%) and PC2 (16.3%) explaining 42.7% of total variation.



CONCLUSION

This comprehensive analysis demonstrated significant genetic variability among genotypes for drought tolerance-related traits, emphasizing the potential for selection in breeding programs. Traits such as relative water content, chlorophyll content (NDVI), grain yield, harvest index and total dry matter showed strong positive correlations, underscoring their interdependence in sustaining productivity under drought stress. The negative correlation of canopy temperature with these traits further validated its use as a reliable indicator of plant stress. PCA effectively identified key trait groupings and dimensional reductions, with grain yield, harvest index, RWC, and total dry matter emerging as major contributors to drought resilience. The contrasting behavior of days to heading and some physiological traits suggests trade-offs in adaptation mechanisms that should be carefully considered in selection strategies. Overall, the integration of morphological and physiological trait data through correlation and multivariate analyses enhances understanding of drought tolerance mechanisms and aids in the identification of robust traits for improving drought resilience in breeding programs. These insights provide a solid foundation for advancing genotype selection and the development of high-yielding, drought-tolerant cultivars suited to water-limited agricultural systems.

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