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Research Article

Phenotypic plasticity and drought resilience of sorghum genotypes under soil moisture deficit

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ABSTRACT

Drought stress is a major abiotic constraint limiting crop productivity, particularly in arid and semi-arid regions. This study evaluated the performance of 60 sorghum genotypes under three soil moisture regimes: control (100% field capacity), moderate stress (75% field capacity), and severe stress (50% field capacity). Analysis of variance (ANOVA) revealed highly significant differences ($p < 0.01$) among genotypes for all morpho-physiological traits, highlighting the strong influence of soil moisture deficit on plant growth and development. Progressive drought stress consistently reduced plant height, leaf area, leaf number, fresh and dry biomass, relative water content, chlorophyll content, and cell membrane stability. However, genotypes S-2, 1863, and Sargodha-2011 exhibited superior performance across all moisture regimes, indicating their potential drought tolerance. In contrast, genotypes 74724, GD-65122, and 3484 were most adversely affected under water-deficit conditions. Cluster analysis classified the genotypes into three subgroups based on their drought tolerance potential, while correlation analysis revealed strong positive associations among key growth traits. Genotypic and phenotypic correlation estimates further confirmed the genetic control of plant height, leaf area, fresh biomass, and cell membrane stability, highlighting their importance as selection criteria for drought tolerance breeding. Overall, these findings provide valuable insights into the genetic basis of drought response in sorghum and support targeted breeding strategies to enhance drought resilience in cereal crops.

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Introduction

Soil moisture stress is one of the most critical abiotic constraints limiting agricultural productivity, particularly in rainfed and semi-arid regions. Water availability plays a decisive role in determining crop yield and biomass production. Drought stress disrupts plant water status by restricting root water uptake, which reduces transpiration and photosynthesis (Schulze, 1986; Anjum et al., 2011). In semi-arid regions, where rainfall is scarce,

erratic, and unevenly distributed, drought is a major factor constraining crop productivity. These regions cover approximately 41% of the Earth's land area and are home to more than 2 billion people, many of whom depend directly on rainfed agriculture for their livelihoods (FAO, 2019). Limited water availability in such environments not only lowers yields but also threatens food security, economic stability, and the sustainability of farming systems (Lobell et al., 2008). Increasing water scarcity has

therefore become a primary challenge for crop establishment in these regions, posing a significant threat to global food security (Rao et al., 2018).

The cultivation of resilient crops such as sorghum is essential for maintaining agricultural productivity under drought-prone conditions (Paterson et al., 2009). Sorghum (*Sorghum bicolor* L.) is a highly adaptable cereal crop cultivated worldwide for food, animal feed, and diverse industrial applications. In semi-arid regions of Africa and Asia, it serves as a staple food and provides a vital source of energy, protein, minerals, and vitamins to millions of people (FAO, 1995; Paterson et al., 2009). Its resilience to drought and high temperatures highlights its importance in sustaining food security under water-limited conditions. Globally, sorghum ranks as the fifth most widely grown grain crop by tonnage, after maize, wheat, rice, and barley, owing to its high biomass yield and adaptability to stress-prone environments (Almodares et al., 2007; Ogbaga et al., 2014).

According to USDA (2023), global sorghum cultivation in 2022-2023 covered 40.64 million hectares, producing 57.60 million tons. In Pakistan, sorghum occupied about 0.22 million hectares, with a production of 0.14 million tons during the same period, highlighting its economic importance. Sorghum's superior adaptation to abiotic stresses is largely attributed to its physiological, morphological, and genetic traits, including a deep root system, reduced stomatal conductance, and efficient water-use mechanisms (Farooq et al., 2009; Xin et al., 2009). Moreover, osmotic adjustment and a strong antioxidant defense system help sorghum mitigate oxidative damage under stress (Choudhary et al., 2022).

With the ongoing impacts of climate change, rising temperatures, erratic rainfall patterns, and soil degradation, the role of drought-tolerant crops such as sorghum is becoming increasingly critical (Fahmy et al., 2010; Brouk and Bean, 2024). Sorghum's ability to thrive under water-limited and high-temperature environments makes it a promising candidate for sustaining global food security (El Naim et al., 2012; Punia et al., 2020). The projected global population of over 9 billion by 2050 will further intensify the demand for staple crops and livestock feed. Sorghum's high biomass yield and nutritional value position it as an important food, feed, and industrial resource (Paterson et al., 2009; Xiao et al., 2013).

Studies have shown that sorghum genotypes with enhanced drought tolerance maintain higher water-use efficiency and improved biomass partitioning under water-limited

conditions (Borrell et al., 2014). Breeding efforts, both conventional and molecular, have led to the development of drought-tolerant cultivars capable of sustaining productivity under moisture stress (Harris et al., 2007).

Photosynthesis, the fundamental process driving plant growth and productivity, is highly sensitive to water availability. Under drought conditions, reduced leaf water potential leads to stomatal closure, limiting CO₂ uptake and reducing photosynthetic efficiency (Chaves et al., 2009). Sorghum, however, exhibits unique metabolic adaptations and carbon fixation pathways that enable higher photosynthetic efficiency under stress (Wang et al., 2021). Genetic diversity within sorghum further contributes to variation in drought tolerance, with biomass production and partitioning serving as useful indicators of relative tolerance (Edwards et al., 2016). Selective breeding programs have identified drought-tolerant genotypes with improved photosynthetic capacity and water-use efficiency (Somegowda et al., 2024).

Abiotic stresses, particularly soil moisture deficits, continue to challenge global food production. Sorghum's adaptability to adverse environments, coupled with its genetic potential for stress tolerance, underscores its role in sustainable agriculture. Advances in molecular breeding, genetic engineering, and agronomic management have enhanced its resilience, while genomic innovations have yielded genetically modified varieties with improved drought tolerance (Weldemichael et al., 2024). As climate change continues to threaten agricultural systems, the cultivation of sorghum remains vital for meeting the nutritional and economic demands of a growing population.

The present study was therefore undertaken to evaluate and characterize sorghum genotypes under varying levels of soil moisture deficit, with the aim of identifying climate-resilient genotypes for sustainable agriculture.

Materials and Methods

A total of sixty sorghum genotypes were obtained from two institutions: the Fodder Research Institute (FRI), Sargodha, and the National Agricultural Research Centre (NARC), Islamabad, Pakistan (Table 1). These genotypes were systematically screened and evaluated under varying soil moisture conditions through a controlled pot experiment conducted at the Department of Plant Breeding and Genetics, Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Pakistan, during the Spring season of 2018.

Table 1. Sorghum genotypes evaluated under soil moisture stress.

Sr. No.	Genotype	Sr. No.	Genotype	Sr. No.	Genotype	Sr. No.	Genotype
1	YSS-98	16	FRI-04	31	74702	46	JS-2002
2	39501	17	3484	32	80027	47	Turbo
3	74724	18	FM-147	33	80230	48	I-8
4	Ballo	19	Hegari	34	3651	49	Neeli Bar
5	PARC-SS-2	20	I-7	35	PARC-SS-1	50	YSS15
6	GD-65122	21	YSS-4	36	S-9902	51	1623
7	FM-48	22	I-15	37	PARC-SV-1	52	FRI-07
8	S-2	23	YSS-1	38	FRI-06	53	80022
9	I-1	24	PARC-SS-3	39	I-9	54	S-9905
10	Sargodha 2011	25	I-3	40	1828	55	403415
11	I-5	26	PARC-SV-4	41	1863	56	F-2008
12	PARC-SV-2	27	I-13	42	SD-167	57	JS263
13	JS-2007	28	I-4	43	A-113	58	S-20016
14	1744	29	Sweet	44	Sandal Bar	59	S-9901
15	YSS-13	30	80010	45	I-6	60	A-3949

The experiment was laid out in a completely randomized design (CRD) with a two-factor factorial arrangement and three replications in a rain-protected environment. Standardized plastic pots (35 cm height × 18 cm diameter) were used. The soil used was sandy loam, free from plant propagules and inert materials, and sun-dried prior to use. The soil was thoroughly mixed with the recommended dose of fertilizer, calculated on a soil weight basis. The recommended dose was 70-57-62 kg NPK ha⁻¹, considering one hectare of soil (15 cm depth) equivalent to 3 × 10⁶ kg. Accordingly, each pot (6 kg soil) received 0.31 g urea, 0.25 g triple superphosphate (TSP), and 0.21 g muriate of potash (MP).

Three soil moisture regimes were imposed to simulate drought stress:

1. Control (C) = 100% field capacity (no drought stress).
2. Moderate stress (M1) = 75% field capacity (mild drought stress).
3. Severe stress (M2) = 50% field capacity (severe drought stress).

Soil moisture levels were maintained through weekly irrigation based on the measured soil moisture content by weight. Ten seeds of each genotype were sown at a depth of 1 cm on March 15, 2018. After emergence, seedlings were thinned to five plants per pot at 15 days after emergence. Plants were harvested 75 days after sowing (May 28, 2018) to record fodder yield data, as described below.

Agro-physiological, biochemical, and plant growth measurements

Plant height

Plant height was recorded at harvest by measuring, with a measuring scale, the distance from the plant base to the tip of the longest leaf in each treatment. The mean value was then calculated.

Number of leaves per plant

At harvest, the total number of leaves per plant was counted for each treatment, and the average value was calculated to assess differences among genotypes.

Leaf area (cm²)

Leaf area (LA) was estimated at harvest by measuring the length and maximum width of the central leaf of plants in each treatment. The leaf area was calculated using the given below formula as described by Montgomery (1911) and Stickler et al. (1961):

$$\text{Leaf Area} = (\text{Leaf length} \times \text{Max. leaf width}) \times 0.75$$

Fresh plant weight (g)

After harvest, five plants were randomly selected from each treatment; weighed using an electronic balance to determine fresh weight, and the average value was calculated.

Dry plant weight (g)

Following fresh weight determination, the plant material was cut into small pieces and oven-dried at 70°C for 48 h to remove moisture. The dried samples were then cooled in a desiccator and weighed using an electronic balance to determine dry plant weight.

Brix value (°Bx)

The Brix value, an indicator of sugar concentration in plant sap, was measured using a handheld refractometer. Sap was extracted from five randomly selected plants per treatment for analysis.

Chlorophyll content (SPAD Units)

Chlorophyll content was measured using a SPAD-502 Plus chlorophyll meter, which determines leaf absorbance in the 400-500 nm (blue) and 600-700 nm (red) wavelength ranges. Measurements were obtained by inserting a leaf into the sensor slot, and the corresponding SPAD values were recorded.

Relative water content (RWC)

Relative water content (RWC) was determined following Browne et al. (2020). Leaf samples (1 × 7 cm) were excised from the mid-vein region, and their fresh weight (FW) was recorded immediately. Samples were then rehydrated in distilled water for 24 h to obtain turgid weight (TW), followed by oven drying at 70°C for 48 h to determine dry weight (DW). RWC was calculated using the formula described by Barrs and Weatherley (1962) as follows:

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

Cell membrane stability (CMS)

Cell membrane stability was determined following Kamatar and Nayakar (2004). Two sets of 200 mg leaf samples were placed in test tubes containing 10 ml of double-distilled water. The first set was incubated in a water bath at 40°C for 30 min, and the electrical conductivity (C_1) was measured with a conductivity meter. The second set was boiled at 100°C for 10 min, and the conductivity (C_2) was recorded. CMS was calculated as described by Kamatar and Nayakar (2004).

$$\text{CMS (\%)} = \left\{ 1 - \frac{C_1}{C_2} \right\} \times 100$$

Statistical analysis

Data collected for all morpho-physiological traits were subjected to analysis of variance (ANOVA) following the procedure of Steel and Torrie (1986). Treatment effects were tested for significance, and mean comparisons were performed using the Least Significant Difference (LSD) test at the 1% and 5% probability levels to evaluate differences among genotypes, moisture regimes, and their interactions. Cluster analysis was employed to classify sorghum genotypes into distinct groups based on their responses to soil moisture stress, while correlation analysis was used to determine the strength and direction of associations among measured traits.

Results

Analysis of variance (ANOVA) showed highly significant differences ($p < 0.01$) among genotypes for all agronomic and growth traits, indicating that soil moisture stress exerted a substantial influence on these parameters (Table 2).

Effect on morphological traits

Among the agronomic traits, plant height varied significantly among genotypes under different soil moisture regimes. Under control conditions, genotype 1863 attained the greatest height (128.27 cm), whereas 74724 recorded the shortest (67.60 cm). Under moderate drought stress (M1), plant height ranged from 50.40 cm in GD-65122 to 102.47 cm in Sargodha-2011. At severe drought stress (M2), the shortest plants were observed in 74724 (34.93 cm), while S-2 produced the tallest plants (72.13 cm). Overall, across all treatments, genotypes 1863, S-2, and Sargodha-2011 consistently exhibited greater plant height, whereas 74724, GD-65122, and 3484 recorded the lowest values (Figure 1a).

Leaf count was also significantly affected by soil moisture regimes. Under control conditions, genotypes 1863, S-2, and Sargodha-2011 exhibited the highest leaf numbers, while 74724 and GD-65122 produced the lowest. A progressive reduction in leaf count was observed with increasing moisture stress. Under moderate stress (M1), the lowest value (5.40) was recorded in 74724 and 3484, whereas S-2 maintained the highest (9.33). Under severe stress (M2), leaf count ranged from 4.33 (74724) to 8.13 (1863). Across all treatments, genotypes S-2, 1863, and Sargodha-2011 consistently maintained higher leaf counts (Figure 1b).

Similarly, leaf area declined progressively with increasing moisture stress. Under control conditions, S-2 exhibited the maximum leaf area (398.71 cm²), whereas 3484 showed the minimum (92.02 cm²). At 75% field capacity, S-2 maintained the highest leaf area (309.64 cm²), while 3484 recorded the lowest (72.64 cm²). At 50% field capacity, the maximum leaf area was again observed in S-2 (214.20 cm²), whereas GD-65122 exhibited the minimum (47.81 cm²) (Figure 1c).

Fresh plant weight also decreased under stress conditions. Under control conditions, Sandal Bar (96.06 g), PARC-SV-4 (95.02 g), and S-2 (94.95 g) recorded the highest fresh weights, while I-1 showed the lowest (51.78 g). Under moderate stress, fresh weight ranged

from 25.81 g (3484) to 65.07 g (YSS1), with S-2 maintaining relatively higher performance. Under severe stress, fresh weight further decreased, ranging from 11.62 g (GD-65122) to 39.22 g (S-2) (Figure 1d).

Dry plant weight followed a similar trend, with FM-147, Sandal Bar, and 80010 producing the highest values, while genotypes such as 74724 consistently recorded the lowest dry weights across all treatments (Figure 1e).

Table 2. Mean square values of sixty sorghum genotypes evaluated under three soil moisture levels.

SOV	DF	PH	LP	LA	FW	DW	BV	CC	CMS	RWC
Gen	59	1677.40**	7.21**	26477**	851.22**	90.28**	14.29**	42.69**	30.20**	223.6**
Stress	2	66084.10**	100.68**	402615**	98210.60**	6394.57**	13.05**	664.33**	30464.0**	56845.7**
G × S	118	80.50**	0.12 ^{ns}	914*	82.42**	6.76**	0.21 ^{ns}	1.27**	3.30**	19.8*
Error	358	19.50	0.11	177	4.84	1.14	1.15	1.56	1.62	21.3

SOV = Source of variance; DF = Degrees of freedom; PH = Plant height; LP = Leaves per plant; LA = Leaf area; FW = Fresh weight; DW = Dry weight; BV = Brix value; CC = Chlorophyll content; CMS = Cell membrane stability; RWC = Relative water content. Significance levels: * = $p < 0.05$; ** = $p < 0.01$; ns = Non-significant ($p \geq 0.05$).

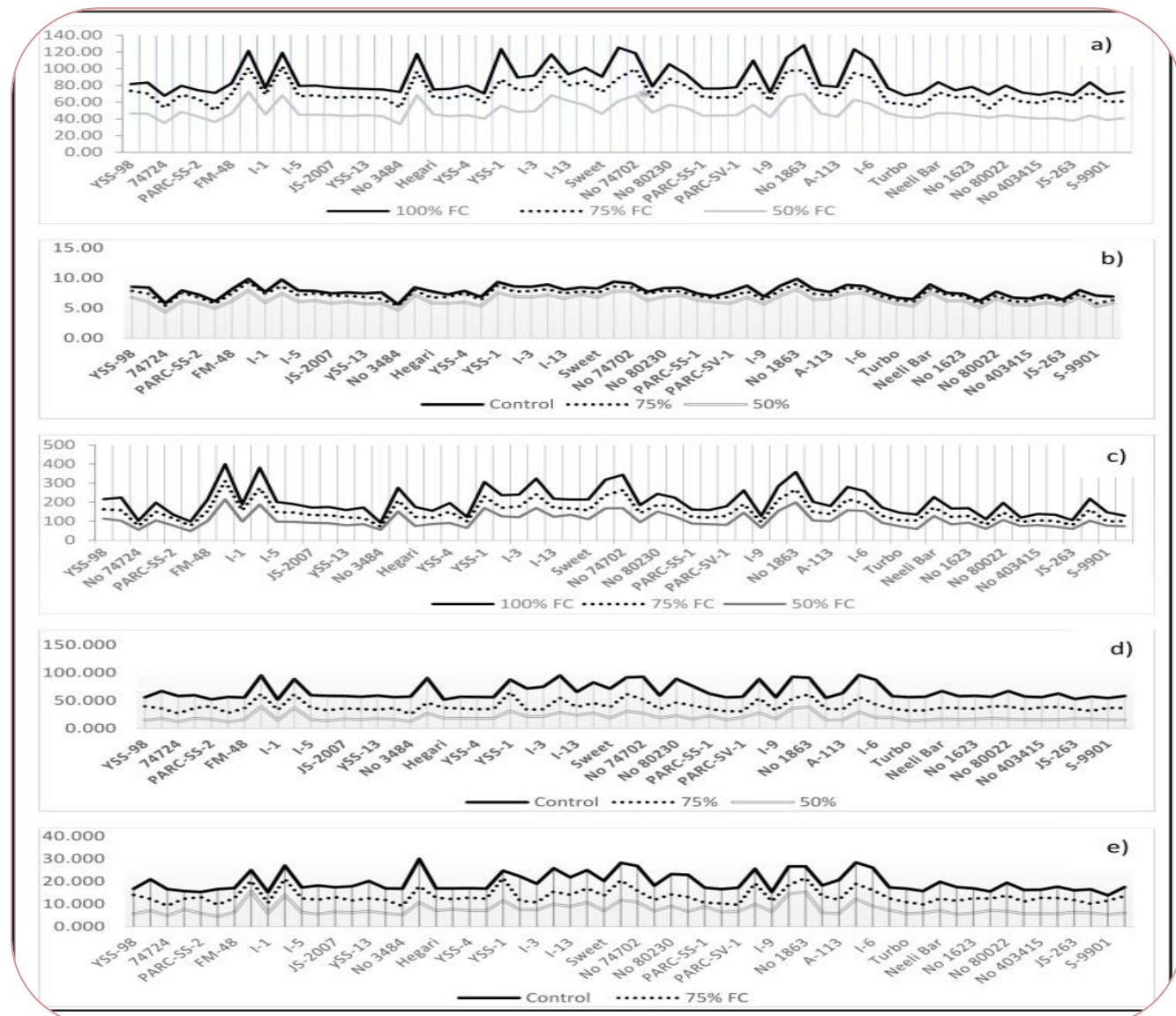


Figure 1. Morphological traits under varying soil moisture stress levels.

Cluster analysis

Cluster analysis grouped the genotypes into three major subclusters based on morpho-physiological parameters, confirming the effectiveness of dendrogram-based selection for distinguishing drought-tolerant and susceptible sorghum genotypes (Figure 3). Subcluster I comprised 14 genotypes exhibiting high

tolerance to water deficit, characterized by superior plant height, leaf area, fresh and dry biomass, chlorophyll content, and cell membrane stability. Subcluster II consisted of 23 genotypes with intermediate drought tolerance, whereas Subcluster III comprised 23 genotypes that were susceptible to water deficit (Table 3).

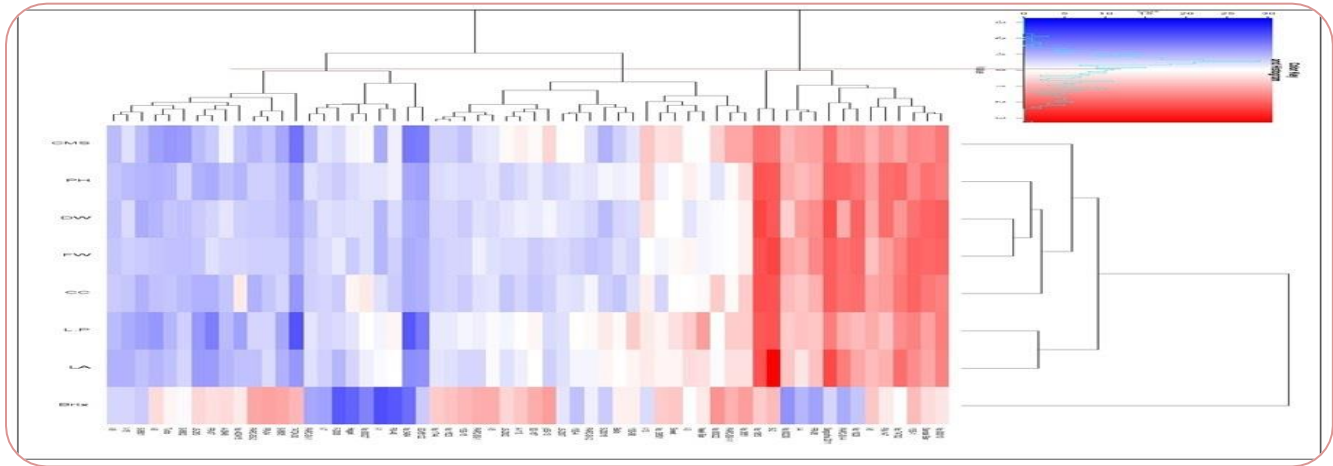


Figure 3. Heatmap and dendrogram of sixty sorghum genotypes based on morpho-physiological traits.

Table 3. Average cluster values of eight morpho-physiological traits under three moisture treatments.

Clusters	PH (cm)	LP	LA (cm²)	FW (g)	DW (g)	Brix (°Br)	CC (SPAD units)	CMS (%)	RWC (%)
Cluster 1	91.33	8.28	232.56	58.49	18.85	14.94	23.09	43.80	79.37
Cluster 2	66.02	7.26	152.56	38.71	12.63	15.72	19.02	41.93	73.72
Cluster 3	58.48	6.31	104.08	35.47	11.33	14.54	18.19	40.75	68.47

PH = Plant Height; LP = Leaves Per Plant; LA = Leaf Area; FW = Fresh weight; Brix = Brix value; DW = Dry weight; CC = Chlorophyll Content; CMS = Cell Membrane Stability; RWC = Relative water content.

Pearson correlation

Genotypic correlations under varying moisture stress conditions

Correlation analysis revealed that, under control conditions, plant height showed highly significant positive associations with leaf area, number of leaves per plant, fresh and dry biomass, cell membrane stability (CMS), and chlorophyll content, but no correlation with Brix. Leaf area and number of leaves per plant were also strongly correlated with biomass, CMS, and chlorophyll, while fresh and dry biomass were closely associated with CMS and chlorophyll. The strongest correlation was observed between CMS and chlorophyll. By contrast, Brix showed no significant correlation with any trait, indicating its independence from growth- and physiology-related parameters (Figure 4a). Similar patterns were observed under water-deficit conditions at 75% field capacity (Figure 4b) and 50% field capacity (Figure 4c). Plant height, leaf area, and

number of leaves per plant consistently maintained significant positive correlations with biomass, CMS, and chlorophyll, while fresh and dry biomass were strongly interrelated and closely associated with physiological traits. CMS and chlorophyll exhibited the strongest correlations across all water regimes, highlighting their co-regulation under stress. In contrast, Brix consistently showed non-significant associations with other parameters, confirming its distinct role as a sugar concentration trait, independent of morpho-physiological growth attributes. Phenotypic correlations under varying moisture stress conditions At the phenotypic level, correlation analysis revealed that plant height, leaf area, number of leaves per plant, fresh and dry biomass, CMS, and chlorophyll content were strongly and positively associated under control, moderate (75% FC), and severe (50% FC) water-deficit conditions (Figures 4d-f).

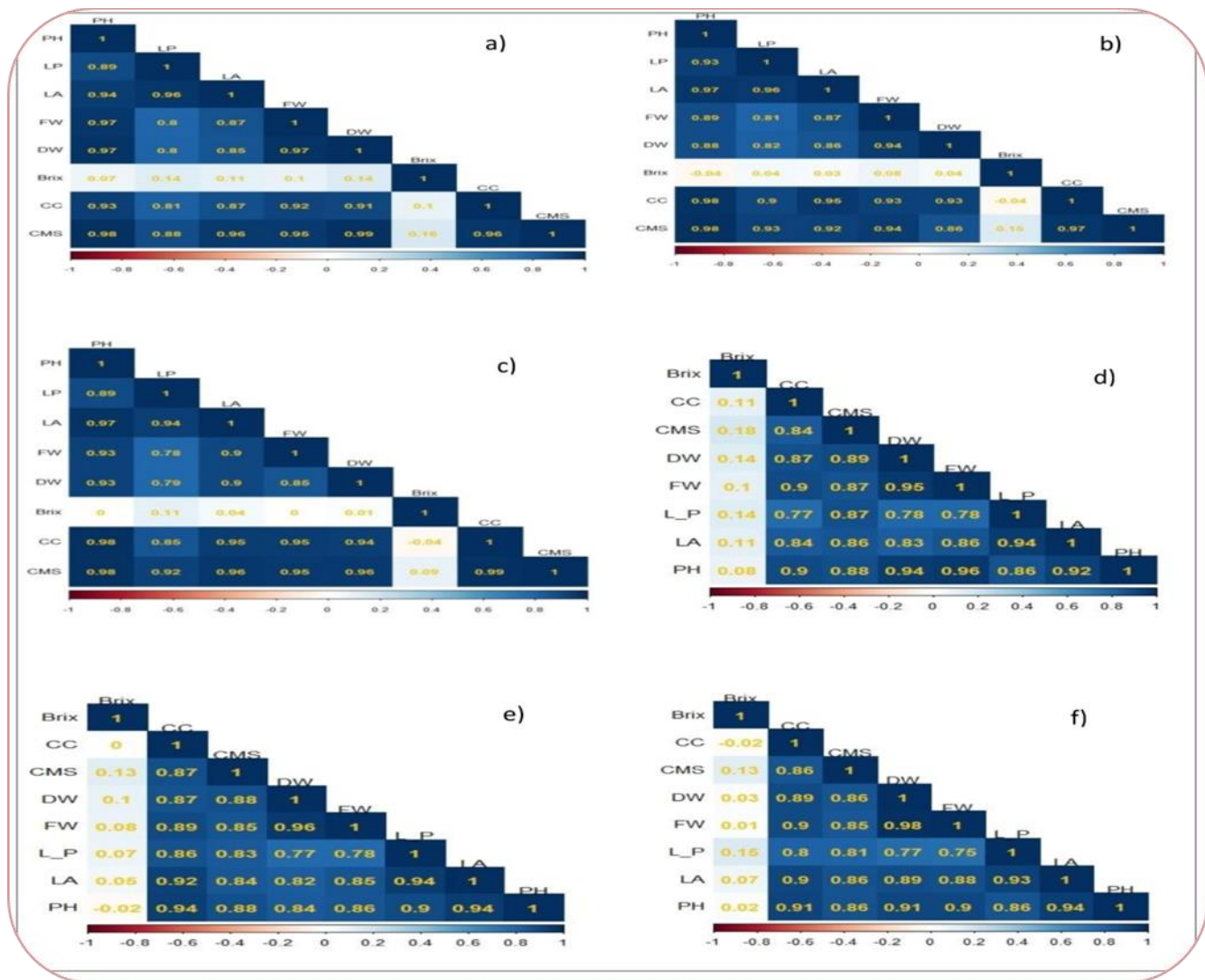


Figure 4. Phenotypic and genotypic correlations under varying soil moisture stress levels.

These consistent associations suggest that traits contributing to biomass production are co-regulated with photosynthetic capacity and membrane integrity, highlighting their collective role in sustaining growth under moisture stress. The strongest correlations were found between CMS, chlorophyll content, and biomass traits, indicating that membrane stability and chlorophyll retention directly influence growth performance under drought conditions. In contrast, the Brix value showed no correlation with other traits across all soil moisture regimes, confirming its independence from morpho-physiological growth attributes. This supports the view that sugar accumulation in sorghum under water deficit reflects osmotic adjustment and metabolic partitioning mechanisms rather than direct contributions to biomass production.

Discussion

Drought stress is one of the major constraints affecting sorghum productivity worldwide, particularly in arid and semi-arid regions. This study provides valuable insights into the morphological and physiological responses of sorghum genotypes under varying soil moisture stress levels and highlights key traits that contribute to drought tolerance. The reductions in plant height, number of leaves, and leaf area under moderate (M1) and severe (M2) drought stress confirm the detrimental impact of soil moisture deficits on vegetative growth. These findings are consistent with previous reports documenting significant declines in plant height and leaf area as major effects of water scarcity in sorghum (Hussein and Alva, 2014; Perrier et al., 2017). The tallest genotypes, such as 1863 and S-2,

maintained superior growth under both moderate and severe drought stress, suggesting their potential value in breeding programs targeting drought resilience. Similarly, genotypes with larger leaf areas under control conditions, such as S-2 and Sargodha-2011, retained relatively higher leaf area under stress, supporting earlier findings that emphasized the role of leaf area in regulating transpiration and improving water-use efficiency (Mwamahonje et al., 2021).

Moisture stress also significantly reduced fresh and dry biomass accumulation, consistent with earlier reports attributing biomass declines in sorghum to reduced carbon assimilation and metabolic activity under drought (Habyarimana et al., 2004; Hud et al., 2016). Nevertheless, genotypes such as S-2 and 1863 sustained relatively higher biomass under stress, indicating adaptive mechanisms such as efficient water uptake or osmotic adjustment. Previous studies in West Africa similarly reported up to 49% reductions in plant height, 7-9% decreases in leaf number, and 18-28% reductions in straw dry matter under drought (Gano et al., 2021). Controlled-environment phenotyping further confirmed drastic reductions in stem and leaf biomass (62% and 55%, respectively) and leaf area loss during late vegetative stages, reflecting adaptive strategies to reduce transpiration under water scarcity (Tovignan et al., 2023). Collectively, these results indicate that genotypic differences in vegetative growth and biomass maintenance under drought stress are critical indicators of drought tolerance in sorghum.

Brix value, reflecting sugar content and potential forage quality, showed a slight increase under drought as water limitation concentrated soluble sugars and promoted osmotic adjustment, but remained relatively stable overall. This suggests that sugar accumulation is less affected by drought than other traits, pointing to stronger genetic control and lower environmental influence (Foyer et al., 1994). Unlike biomass or photosynthetic traits, Brix often acts independently, reflecting osmotic adjustment and sugar partitioning rather than direct growth performance (Almodares et al., 2013; Appiah-Nkansah et al., 2019; Motsi et al., 2022). For instance, Zegada-Lizarazu and Monti (2013) noted that higher sugar levels in drought-stressed sorghum stems may protect photosystem II. Similarly, Perrier et al. (2017) reported increases in soluble sugars despite biomass reduction. Tovignan et al. (2020) also showed that post-anthesis drought decreased stem sucrose but increased hexoses,

with no change in total sugars, reflecting shifts in sugar partitioning for osmotic adjustment. Collectively, these findings indicate that drought typically reduces biomass but promotes sugar accumulation, largely independent of growth-related traits.

Cell membrane stability (CMS) decreased with increasing drought severity, reflecting dehydration-induced disruption of membrane integrity and increased electrolyte leakage. CMS is widely used as a screening criterion for drought tolerance, with lower CMS values indicating greater stress (Takele, 2010; Bajji et al., 2002; Abu-Ria et al., 2024). In this study, genotypes such as Sargodha-2011 and 1863 exhibited higher CMS, suggesting better protection against cellular damage under drought. These results agree with earlier reports highlighting the role of CMS in maintaining membrane integrity and reducing ion leakage during osmotic stress (Masood et al., 2015). The positive correlation between CMS and chlorophyll content further supports CMS as a key indicator of drought resilience (Jabereldar et al., 2017).

Chlorophyll content also declined under drought stress as water limitation accelerated degradation and/or suppressed synthesis, thereby reducing photosynthetic efficiency. However, tolerant “stay-green” genotypes showed a slower decline. Numerous studies confirm significant reductions in total chlorophyll, chlorophyll *a*, and chlorophyll *b* under drought (Borrell et al., 2014; Zhang et al., 2019; Abreha et al., 2022). Drought-sensitive genotypes such as 74724 and GD-65122 exhibited marked decreases, reflecting greater susceptibility to oxidative stress and chlorophyll breakdown (Masood et al., 2015). In contrast, tolerant genotypes like 1863 and S-2 maintained higher chlorophyll levels, prolonging photosynthesis, delaying senescence, and supporting higher biomass and yield (Mwamahonje et al., 2021). Similarly, relative water content (RWC) decreased under drought, but tolerant genotypes maintained higher values and recovered more effectively after rewatering (Premachandra et al., 1995; Goche et al., 2020).

Hierarchical clustering analysis revealed three major clusters based on morpho-physiological traits. Subcluster-I contained the most drought-tolerant genotypes, characterized by greater height, larger leaf area, higher biomass, and greater chlorophyll content. These results align with previous studies that categorized sorghum genotypes into tolerance groups using phenotypic or molecular traits (Kharrazi and Rad, 2011; Derese et al., 2018; Zarea et al., 2024; Wang et al.,

2025). Genotypes in Subcluster-I likely possess adaptive mechanisms such as osmotic adjustment, enhanced rooting, and improved water-use efficiency, providing valuable resources for breeding drought-resilient cultivars.

Strong positive correlations among plant height, leaf area, fresh and dry biomass, chlorophyll content, and CMS suggest that these traits can be jointly targeted to improve drought tolerance. The absence of significant correlation between Brix and other traits supports its independence and limited utility as a selection criterion for drought tolerance (Adugna, 2014). Genotypic correlation estimates consistently exceeded phenotypic ones, highlighting the predominance of genetic factors over environmental influences. This emphasizes the potential for genetic improvement through selection and breeding strategies aimed at enhancing multiple drought-tolerance traits simultaneously (Abebe et al., 2020; Arodi, 2020).

This study thus provides important insights into the genetic diversity and drought responses of sorghum genotypes under varying soil moisture conditions. The identification of drought-tolerant genotypes, particularly those in Subcluster-I, demonstrates the potential for targeted breeding. Key traits such as plant height, leaf area, chlorophyll content, and CMS emerged as strong indicators of drought tolerance and should be prioritized in sorghum improvement programs. Future research should focus on uncovering molecular and physiological mechanisms underlying drought tolerance, including root architecture, osmotic adjustment, and antioxidant defense. Genome-wide association studies (GWAS) and marker-assisted selection (MAS) will further aid in identifying drought-related loci, accelerating the development of high-yielding, drought-resilient sorghum cultivars for water-limited regions.

Conclusions and Recommendations

In this study, 60 sorghum genotypes were evaluated under three moisture stress conditions, and drought-tolerant genotypes were identified based on stable and heritable traits. Three robust genotypes, Sargodha-2011, 1863, and S-2, emerged as superior performers under drought. These genotypes represent valuable baseline material for breeding programs aimed at developing sorghum cultivars with enhanced drought tolerance, thereby contributing to improved crop productivity in water-scarce regions.

Authors' Contributions

GS, ZA, and MA conceived and supervised the study; MI prepared the experimental materials, collected and analyzed the data, and drafted the initial version of the manuscript; GS provided critical feedback, extensive review, and substantial revisions; All authors contributed to improving the manuscript, thoroughly reviewed the final version, and approved it for submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger

SDG 12: Responsible Consumption and Production

SDG 13: Climate Action

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