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Early Assessment of Drought Tolerance in Cotton Genotypes at seedling stage

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SUMMARY

Cotton stands out as the primary cash crop in Pakistan's agricultural sector. However, cotton productivity has declined due to water scarcity and recent climate fluctuations. In this study, 40 different cotton genotypes were screened at three different moisture levels - 100%, 75%, and 50% of field capacity - in triplicate arrangements. The screening process used a split-plot design within a completely randomized framework during the seedling stage. The data was analyzed using split-plot design analysis of variance, with additional scrutiny through radar and principal component analysis to identify drought-tolerant and susceptible genotypes. Significant variations were observed among genotypes for all measured traits under the three moisture levels. Seedling characteristics such as root length, shoot fresh weight, shoot dry weight, root fresh weight, lateral root number, and excised leaf water loss emerged as highly effective indicators for selection under water deficit conditions during the seedling stage. Notably, the genotypes IUB-212, FH-142, NIAB-111, IR-3701, NS-121, VH-295, VH-144, AA-802, FH-113, and IR-3 demonstrated superior performance at 100% of field capacity. At 75% of field capacity, VH-295, NIAB-111, VH-144, IR-3701, IUB-212, and NS-121 exhibited commendable performance, while at 50% of field capacity, IUB-212, NS-121, NIAB-111, FH-142, MNH-886, FH-113, VH-295, VH-144, and VH-283 showcased resilience to drought. Notably, VH-295, IUB-212, and VH-144 consistently outperformed other genotypes, whereas FH-1000 and CIM-443 demonstrated poor performance across all three moisture conditions. These results provide valuable insights into the drought tolerance of specific cotton genotypes and can guide further research and potential agricultural applications.

Key words: Cotton, water deficit, field capacity, principle component analysis, seedling

INTRODUCTION

Globally, Cotton (*Gossypium hirsutum* L.) is a significant fiber-producing crop and is the second-ranked oilseed crop following soybean (Jones and Kersey 2002). In Pakistan, Cotton holds a crucial position as a cash crop and a primary contributor to foreign exchange earnings. Its cultivation supports various sectors, including agriculture, ginning factories, textile mills, and business ventures (Imran et al. 2011). Contributing 2.0 percent to the GDP and 8.2 percent to agriculture value addition, Pakistan positioned as the fourth-largest cotton-producing country globally (Pakistan. 2021-22). However, under the current conditions of climate change, the production of cotton faces significant fluctuations due to a range of biotic and abiotic stresses. Notably, water deficiency stands out as a critical factor leading to a decline in seed cotton yield (Hu et al. 2018). The scarcity of irrigation water in Pakistan has notably diminished the seed cotton yield per unit area. The escalating demand for irrigation water, coupled with decreasing availability due to high losses in irrigation and insufficient rainfall, poses a substantial threat to maintaining adequate moisture levels for crop production.

There is a severe impact of drought on cotton plant development, output, and quality characteristics (Ali and Ahmadikhah 2009). Under drought conditions, plants undergo a variety of morphological changes, including reductions in leaf area, reductions in stomata frequency, thickening of leaf cell walls, deposition of wax in epicuticles, development of conductive systems, increased frequency of large vessels, senescence prior to maturity, and formation of leaves in cereals with a tube-like structure (Ahmad et al. 2009). Drought is also caused by high temperatures, which impede photosynthesis by increasing the rate of evapotranspiration. Drought is the most challenging and complicated abiotic stress on agricultural output since it is polygenic in nature (Meshram et al. 2022).

Developing tolerance against water deficit is crucial and requires a comprehensive understanding of plant responses in such conditions. Plants exhibit various developmental phases like morphological, physiological, biochemical, anatomical, and molecular in response to water deficit challenges (Abdalla and El-Khoshiban 2007). The complexity of the drought tolerance mechanism spans cellular, molecular, and whole-plant levels, influenced by factors such as crop species, stress intensity, and duration, and plant developmental stages (Mahmood et al. 2019). Plants employ diverse survival strategies during drought, often employing multiple tolerance mechanisms simultaneously. The three fundamental mechanisms include: (i) Escape: This involves completing the plant's life cycle before water becomes scarce. (ii) Avoidance or Tolerance: Plants take measures to cope with reduced water supply, such as closing stomatal openings and reducing transpiration rates. (iii) Resistance Mechanism: Plants respond at the cellular level to water deficit conditions by developing antioxidants that help maintain osmotic adjustments. This mechanism also operates at the tissue level (Loka 2012).

It is now well acknowledged that drought tolerance is a complex process that negatively impacts cotton plants when they are still in the seedling stage. The cotton plant's developmental stages may be divided into five primary growth phases: seedling establishment, germination and emergence, leaf area and canopy development, blooming and boll development, and boll maturity. Water stress at the start of the growing season might cause the plant stand to decline since the seedlings will not survive. Extended periods of drought at the seedling stage might have disastrous effects on cotton plants, and water stress during the peak blooming stage is crucial for the production of seed cotton. To maintain blossoms and young bolls, cotton plants require a larger amount of water; nevertheless, during the early stages of seedling development, this moisture demand is rather high (Riaz et al. 2013).

Drought stress has a profound impact on the plant-water dynamics, causing a notable disruption in the balance and resulting in a decrease in total water content along with altered cell turgor. This stress condition induces the closure of stomata, leading to reduced transpiration rates and inhibition of photosynthetic activity, as observed by (Pamungkas and Farid 2022). Physiological indicators such as Relative

Water Content (RWC), which measures the amount of water retained in leaf tissue, play a crucial role under water stress conditions. The maintenance of a higher RWC in leaf tissue is recognized as a dependable selection criterion for the development of crop varieties that are well-suited for cultivation in water-scarce environments, as highlighted by (Rahman et al. 2000).

The selection of cotton genotypes based on seedling characteristics presents an informal, cost-effective, and convenient approach. Moreover, the moderate to high variation in seedling attributes, influenced by additive genetic effects on the environments, as indicated by (Anandan 2010), underscores the importance of such an approach. Against the backdrop of the current climate change scenario, our study aimed to address this by conducting experiments to assess the performance of forty distinct cotton accessions across three moisture levels. The objective is to identify drought-tolerant genotypes based on seedling characteristics. This endeavor holds promise as a potential source for cultivating drought-tolerant cotton in dry land areas characterized by semiarid and rain-fed conditions, ultimately contributing to bolstering cotton production in the country.

MATERIALS AND METHODS

Plant Material and experimentation site

A total of 40 cotton genotypes sourced from various research institutes (Table 1) were planted in polythene bags filled with sandy loam soil with a pH of 7.8 and electrical conductivity (EC) of 1.7 dSm-1. The experimental design followed a split-plot design under a completely randomized arrangement, replicated thrice. At the time of sowing, seeds from each line/variety were soaked overnight, and the next morning, holes were made at a depth of 2.5cm in the polythene bags. Two seeds were planted in each hole. The greenhouse temperature and humidity were maintained at 35°C during germination and growth using hot water circulation in pipes and electric heaters. To achieve a photoperiod of 16 hours, the plants were exposed to natural sunlight supplemented with artificial lighting. Thinning to one plant per bag was carried out two weeks after planting, and every 14 days, 0.25 g of Urea (46% Nitrogen) was added to each bag. Daily watering and, when necessary, spraying was conducted to prevent pest attacks (sucking and chewing). Three moisture levels (100%, 75%, and 50% of field capacity) were implemented based on the calculated field capacity of the soil in bags at the emergence of the first true leaf.

Measuring the seedling traits

Six-week-old seedlings were assessed for various seedling traits, including shoot fresh weight (g), root fresh weight (g), shoot length (cm), root length (cm), shoot dry weight (g), root dry weight (g), lateral root number, and excised leaf water loss (ELWL). To measure these traits, three plants of each genotype from each replication and treatment were carefully removed from the polythene bags and washed to eliminate all sand. Excised leaf water loss was calculated using the formula employed by Matin et al. (1989): ELWL = (Fresh weight - wilted weight) / dry weight. The collected data on seedling traits underwent a simple analysis of variance following the approach outlined by (Steel et al. 1997) using Statistix 8.1. Based on the results obtained from the aforementioned analyses, drought-tolerant genotypes and seedling traits with favorable morpho-physiological characteristics were identified for the selection of drought-tolerant cotton genotypes.

RESULTS AND DISCUSSION

Shoot fresh weight (g)

Mean squares for various traits of screening at the seedling stage are mentioned in Table 2.

The data on shoot fresh weight for all accessions exhibited significant variation, ranging from 1.19 to 2.46g under 100% of field capacity, 1.14 to 2.25 under 75% of field capacity, and 1.07 to 2.19 under 50% of field capacity (Table 3). CIM-443 demonstrated the highest fresh weight (2.46), followed by MNH-147 (2.40) and VH-148 (2.40) under 100% of field capacity, while FH-114 displayed the lowest fresh weight (1.19). At 75% of field capacity, VH-148 exhibited the maximum fresh weight, followed by MNH-147 (2.20) and AS-01 (2.18). Under 50% of field capacity, VH-148 recorded the highest values (2.19), whereas VH-144 displayed the lowest values (1.07) (Fig. 1).

Previous research by scientists such as (Chen et al. 2012) reported shoot fresh weight in various crops, including cotton, under drought conditions. They categorized genotypes as either drought-tolerant or sensitive based on the extent of reduction. In our experiment, all cotton accessions experienced a decrease in shoot fresh weight under drought stress, with FH-1000 exhibiting the highest reduction, indicating its unsuitability as a drought-tolerant genotype. Conversely, VH-148 demonstrated resilience to drought stress, establishing it as a drought-tolerant genotype based on this trait. Accessions VH-148, AS-01, CRS-2007, and CRS-456 performed best in this experiment, while FH-1000, FH-114, and FH-172 were identified as drought-sensitive accessions for this specific trait (Figure 1).

Root fresh weight (g)

The root fresh weight of cotton seedlings is a crucial attribute influenced by water deficit stress, and the recorded values for all accessions are detailed in Table 3. There is significant variation, with values ranging from 0.31 to 0.59, 0.27 to 0.55, and 0.24 to 0.48 under 100%, 75%, and 50% of field capacity, respectively. FH-118 and CRS-2007 exhibited the maximum root fresh weight, both recording values of 0.59, followed by IUB-212 and MNH-147 with values of 0.55. In contrast, AA-802 displayed the minimum value (0.31) under 100% of field capacity. MNH-147 (0.55) and NIAB-111 (0.48) had the highest root fresh weight under 75% of field capacity and 50% of field capacity, respectively (Figure 1). Among the genotypes, CIM-707, IUB-212, MNH-147, and NS-121 were identified as good performers, while FH-175 and FH-172 were deemed poor performers regarding this trait across all three moisture levels. The cotton researchers (Farooq et al. 2019) have suggested that modifications in shoot growth may influence root growth and development, potentially impacting the susceptibility of cotton to water stress.

Shoot length (cm)

In terms of shoot length under 100% of field capacity, FH-118 exhibited the highest shoot length (35.59), followed by MG-6 (34.22) and FH-941 (33.46), while MNH-

886 recorded the lowest shoot length at 20.21. Under 75% of field capacity, shoot length varied from 16.38 (MNH-886) to 30.07 (FH-941), and under 50% of field capacity, it ranged from 17.74 (VH-144) to 26.62 (NS-121) (Table 3). Overall, genotypes IUB-212, FH-118, VH-148, NIAB-111, and NIAB-820 performed better, while MNH-886, AS-01, and MNH-888 performed poorly based on this trait under all three moisture conditions (Figure 2). Consistent with our findings, (Shi et al. 2013) observed a decrease in shoot length in cotton seedlings exposed to drought stress. Many scientists such as (Shah et al. 2011) suggested that modifications in shoot growth may influence root growth and development, potentially impacting the susceptibility of cotton to water stress.

Root length (cm)

The importance of root parameters for water stress tolerance is well established, with researchers highlighting the crucial role of roots under moisture-deficit conditions (Ul-Allah et al. 2021). Root length exhibited significant variation, ranging from 26.29 to 46.59, 21.29 to 38.29, and 15.98 to 36.19 under 100%, 75%, and 50% of field capacity, respectively (Table 3). Under 100% of field capacity, VH-144 (46.59) recorded the maximum root length, followed by KZ-181, FH-114, and NS-121 with values of 45.26, 43.51, and 41.69, respectively. Conversely, CRS-456 (26.29) had the minimum root length, followed by FH-172 (26.71) and FH-175 (28.21). Under 75% of field capacity, VH-148 exhibited the maximum root length (38.39), followed by MNH-147 (37.15) and NIAB-111 (36.38), while CRS-456 (21.29) had the lowest root length, followed by FH-172 (22.71), KZ-181 (23.46), and S-12 (23.85). VH-148 also displayed the maximum root length (36.19) under 50% of field capacity, followed by NS-121 (35.69) and MNH-147 (34.61). In contrast, FH-114 (15.98) had the lowest root length, followed by AA-802 (17.92), VH-295 (18.95), and FH-113 (18.96) (Fig. 2).

In line with our research, studies conducted by (Sabagh et al. 2021) have similarly observed that moderate water stress experienced during the seedling stage results in an augmentation of root length. However, they found that prolonged moisture stress during the reproductive stage hinders root development. Cotton scientists (Luo et al. 2019)further highlighted that genetically modified cotton varieties exhibited heightened tolerance to water stress, attributed to their robust rooting systems in comparison to wild-type cotton.

The significance of deep and extensive root systems as desirable traits for drought adaptation is well-established, contributing to drought resistance across various crop plants. In the context of cotton, diploid species, renowned for their deep root systems, are recognized for their heightened drought tolerance, as outlined by (Mvula et al. 2018). Generally, plants with deep-rooted systems exhibit greater drought tolerance compared to their shallow-rooted counterparts. Consequently, delaying the initiation of the first irrigation in cotton, often up to 40 days, is a common practice aimed at fostering the development of longer roots in natural conditions. This practice allows the roots to explore deep soil layers for moisture, enhancing the plant's ability to withstand drought stress.

Shoot dry weight (g)

In terms of shoot dry weight under 100% of field capacity, AS-01 (0.34) and VH-148 (0.34) exhibited the maximum shoot dry weight, while AA-802 (0.16), followed by VH-144 (0.17) and CIM-240 (0.19), recorded the minimum shoot dry weight. Under 75% of field capacity, NIAB-821 had the maximum value (0.32), and AA-802 had the minimum value (0.15). For 50% of field capacity, IUB-212 had the maximum value (0.27), while FH-941 had the minimum value (0.12) (Table 3). VH-148 and AS-01 were identified as good performers overall, whereas AA-703 was considered a poor performer based on this trait (Fig. 3).

Excised leaf water loss (ELWL%)

The ability of cultivars to exhibit low rates of excised leaf water loss (ELWL%) is indicative of drought resistance, making ELWL% a recommended measure for assessing tolerance to water stresses (Rahman et al. 2000). Cotton genotypes displayed variable responses in ELWL% under water stress during the seedling stage. Under 75% of field capacity, FH-171 recorded the maximum value (0.94), while FH-114 had the minimum value (0.13). Similarly, under 50% of field capacity, CRS-456 had the maximum value (0.90), and FH-114 had the minimum value (0.15) (refer to Table 3). Overall, IR-3 and CRS-456 exhibited higher ELWL%, indicating drought sensitivity, while FH-114 displayed lower ELWL%, signifying drought tolerance across all three moisture levels (see Fig. 3). In line with our findings, (Sarwar et al. 2014) also observed negative effects of water stress on excised leaf water loss under conditions of water shortage.

Root dry weight

In terms of root dry weight, CIM-707 recorded the maximum value (0.13) under 100% of field capacity, FH-171 had the maximum value (0.12) under 75% of field capacity, and IUB-212 had the maximum value (0.10) under 50% of field capacity (refer to Table 3). Specifically, under 50% of field capacity, IUB-212, followed by VH-144 and NIAB-820, performed better, demonstrating drought tolerance, while IR-3 performed poorly, indicating drought sensitivity (see Fig. 4). Consistent with our findings, (Verhoef and Egea 2013) reported that water deficiency during the initial vegetative stage substantially reduces shoot and root dry matter in cotton plants.

Number of lateral roots

The existence of young lateral roots, serving as key sites for water uptake, is recognized as a crucial characteristic in the roots of drought-tolerant plants. Water stress was found to induce noteworthy variations in the development of lateral roots in cotton seedlings, with different genotypes exhibiting distinct responses under water stress conditions. This underscores the importance of lateral root dynamics in the overall response of cotton plants to water stress, highlighting the variability in genotypic responses and potential implications for drought tolerance. Under 75% of field capacity, AA-802 (13.17), followed by FH-142 (13.93) and S-12 (14.86), exhibited a reduction in the number of lateral roots, indicating their drought sensitivity. Similarly, under 50% of field capacity, AS-01 (10.44), followed by AA-802 (11.43) and AA-703 (11.85), displayed a decreased number of lateral roots, further indicating their sensitivity to drought (Table 3). In contrast, the number of lateral roots in varieties like IUB-212 (22.90), FH-171 (22.35), and MNH-147 (18.23) increased under 75% of field capacity, while NIAB-111 (20.98), IUB-212 (20.67), and SB-149 (19.99) showed an increase under 50% of field capacity, revealing their tolerance to water stress. Under both drought stress and control conditions, IUB-212, NS-121, and SB-149 recorded a greater number of lateral roots than the rest of the genotypes (see Fig. 4). The findings from this study align with those of previous research. Basal et al. (2004) also identified two drought-tolerant cotton genotypes, corroborating the notion that certain varieties exhibit resilience to water stress. Similarly, (Mvula et al. 2018) observed that six cotton genotypes exhibited a higher number of lateral roots, suggesting their increased drought tolerance. However, it is noteworthy that (Imran et al. 2011) reported contrasting results, observing that severe water stress led to a reduction in root proliferation. These divergent outcomes underline the complexity of plant responses to water stress, emphasizing the need for a nuanced understanding of genotype-specific reactions to varying levels of water availability.

Table 1: List of 40 cotton accessions used in the current study

Sr. No	Cultivar/Lines	Sr. No	Cultivar/Lines	Sr. No	Cultivar/Lines	Sr. No	Cultivar/Lines
1	AA-703	11	FH-169	21	IR-3	31	MNH-886
2	AA-802	12	FH-170	22	IR-3701	32	NS-121
3	AS-01	13	FH-171	23	IR-901	33	NS-131
4	CRS-2007	14	FH-172	24	IUB-212	34	S-12
5	CRS-456	15	FH-175	25	IUB-222	35	SB-149
6	FH-113	16	CIM-707	26	KZ-181	36	VH-148
7	FH-114	17	CIM-443	27	MG-6	37	VH-144
8	FH-118	18	CIM-240	28	NIAB-111	38	VH-282
9	FH-142	19	MNH-147	29	NIAB-820	39	VH-283
10	FH-1000	20	FH-941	30	MNH-888	40	VH-295

Table 2: Mean squares for various traits of screening at seedling

SOV	D.F	SL	RL	SFW	RFW	SDW	RDW	LRN	ELWL
Trt.	2	1049.592**	2663.160**	3.029**	0.244**	0.113**	0.029*	708.395**	2.243**
Rep(trt)	6	7.502**	6.900**	0.005*	0.002**	0.001**	0.003	7.261**	0.008**
Gen.	39	69.556**	141.020**	1.018**	0.042**	0.017**	0.006**	79.088**	2.214**
Trt*Gen	78	10.638**	32.150**	0.047**	0.003**	0.001**	0.002	4.382**	0.213**
Error	234	1.839	1.31	0.002	0	0	0.002	1.134	0.001

Table 3: Descriptive statistics of seedlings attributes of 40 cotton accessions under 100%FC, 75%FC, and 50%FC

	100%FC				75%FC				50%FC			
Variable	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD
SFW	1.19	2.46	1.88	0.37	1.14	2.25	1.73	0.33	1.07	2.19	1.56	0.36
RFW	0.31	0.59	0.45	0.08	0.27	0.55	0.41	0.07	0.24	0.48	0.36	0.07

SL	20.21	35.59	27.97	3.75	16.38	30.07	25.9	3	17.74	26.62	22.14	2.69
RL	26.29	46.59	35.39	5	21.29	38.29	29.38	4.25	15.98	36.19	26.1	5.03
SDW	0.16	0.34	0.25	0.05	0.15	0.32	0.21	0.05	0.12	0.27	0.19	0.04
RDW	0.05	0.13	0.09	0.02	0.04	0.12	0.08	0.05	0.02	0.1	0.06	0.02
LRN	15.35	26.81	21	3.15	13.17	29.87	19.34	3.29	10.44	20.98	16.22	2.92
ELWL	0.15	0.98	0.96	0.6	0.13	0.94	0.76	0.51	0.15	0.9	0.69	0.51

Table 4: Correlation coefficient among seedling traits under 50% of field capacity.

Traits	EWLW	LRN	RDW	RFW	RL	SDW	SFW
LRN	-0.297**						
RDW	-0.241**	0.455**					
RFW	-0.171**	0.633	0.473**				
RL	-0.221**	-0.586**	0.451**	0.733**			
SDW	-0.08	0.465*	0.463**	0.663	0.625**		
SFW	-0.067	0.389*	0.298	0.731**	0.74	0.657	
SL	0.126*	0.465**	0.382**	0.465*	0.572	0.613**	0.593**

*= Significant, ** = Highly significant, FC = Field capacity, SFW= Shoot fresh weight, RFW= Root fresh weight, SL= Shoot length, RL= Root length, SDW= Shoot dry weight, RDW= Root dry weight, LRN= Lateral root number, ELWL= Excised leaf water loss.

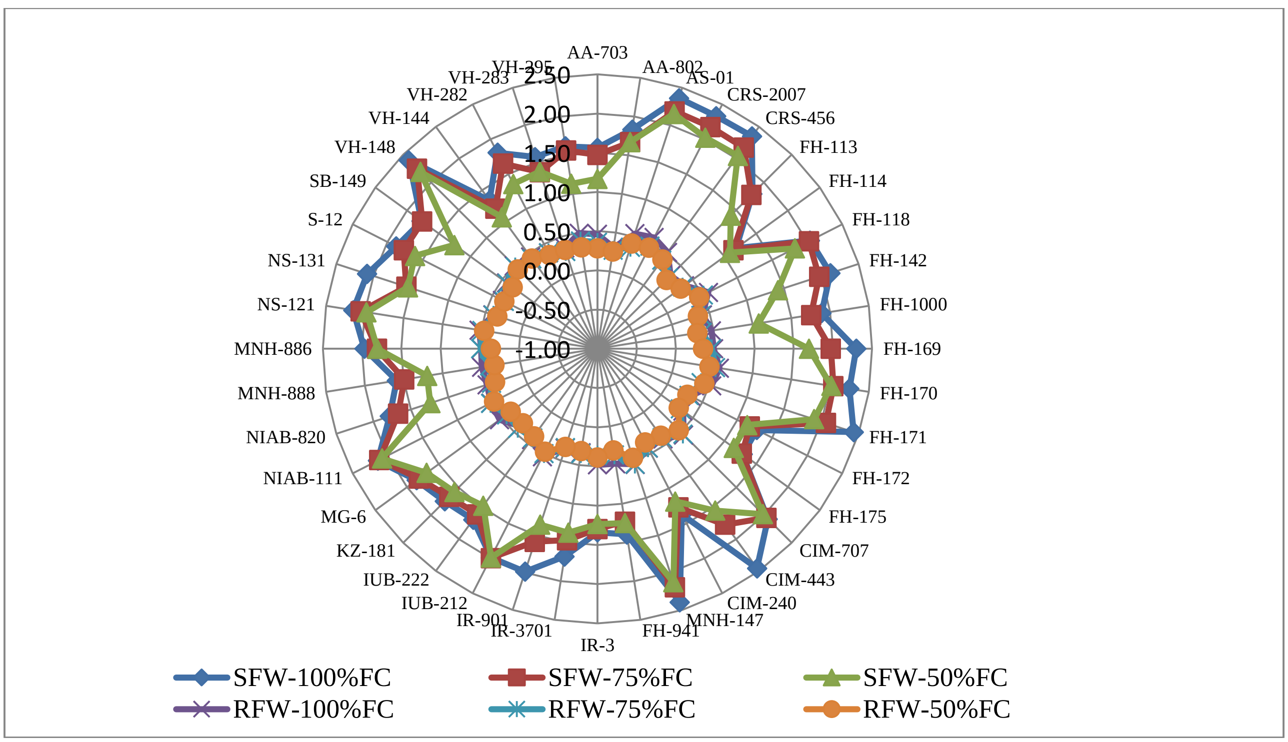

Figure 1: **Behaviors of shoot and root fresh weight of 40 cotton accessions under 100%FC, 75%FC and 50%FC. SFW = Shoot fresh weight, RFW = Root fresh weight, FC = Field capacity.**

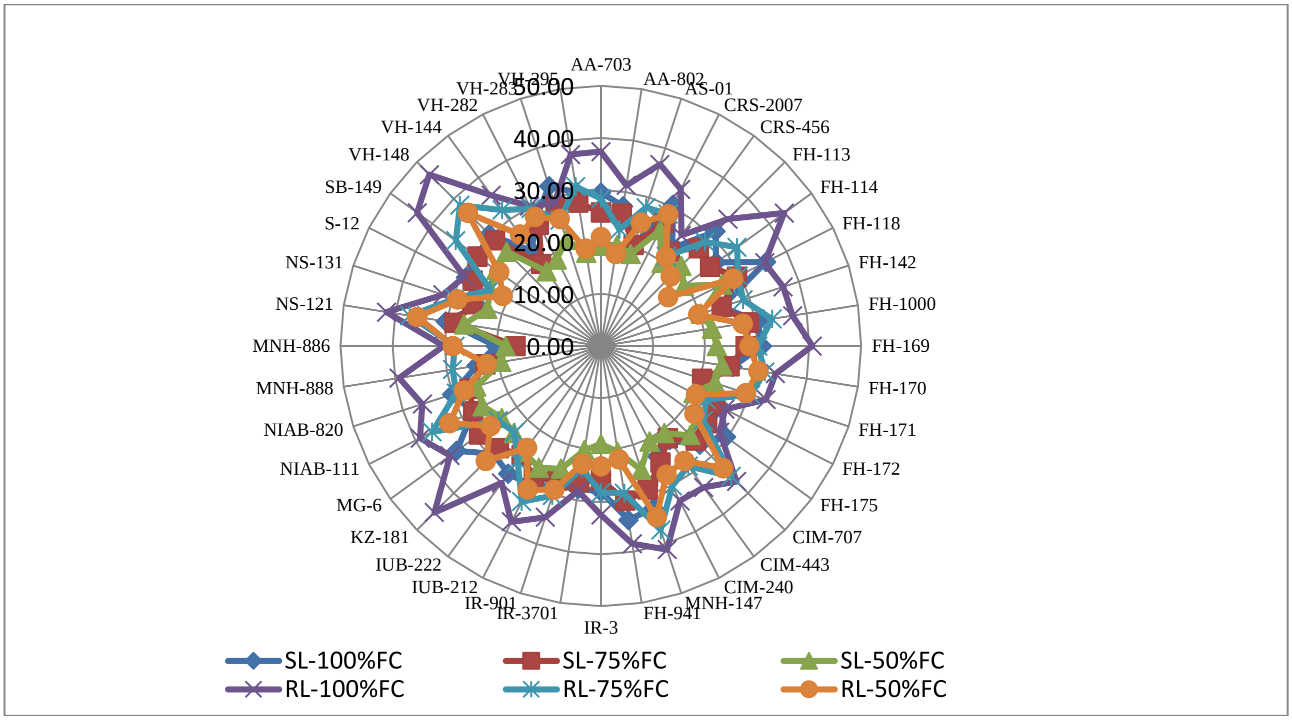

Figure 2: **Behaviors of shoot length and root length of 40 cotton accessions under 100%FC, 75%FC, and 50%FC. SL = Shoot length, RL = Root length, FC = Field capacity.**

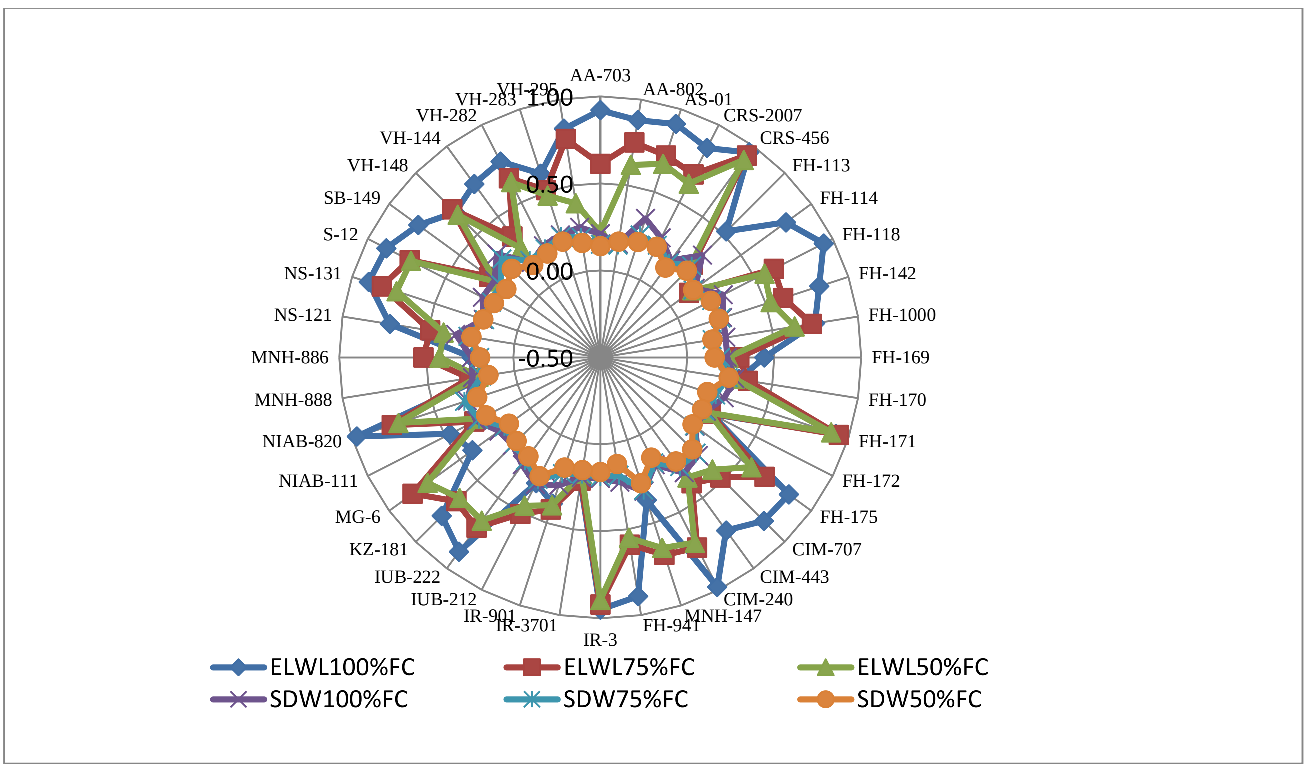

Figure 3: Behaviors of shoot dry weight and excised leaf water content of 40 cotton accessions under 100%FC, 75%FC, and 50%FC. RWC = Relative water content, FC = Field capacity.

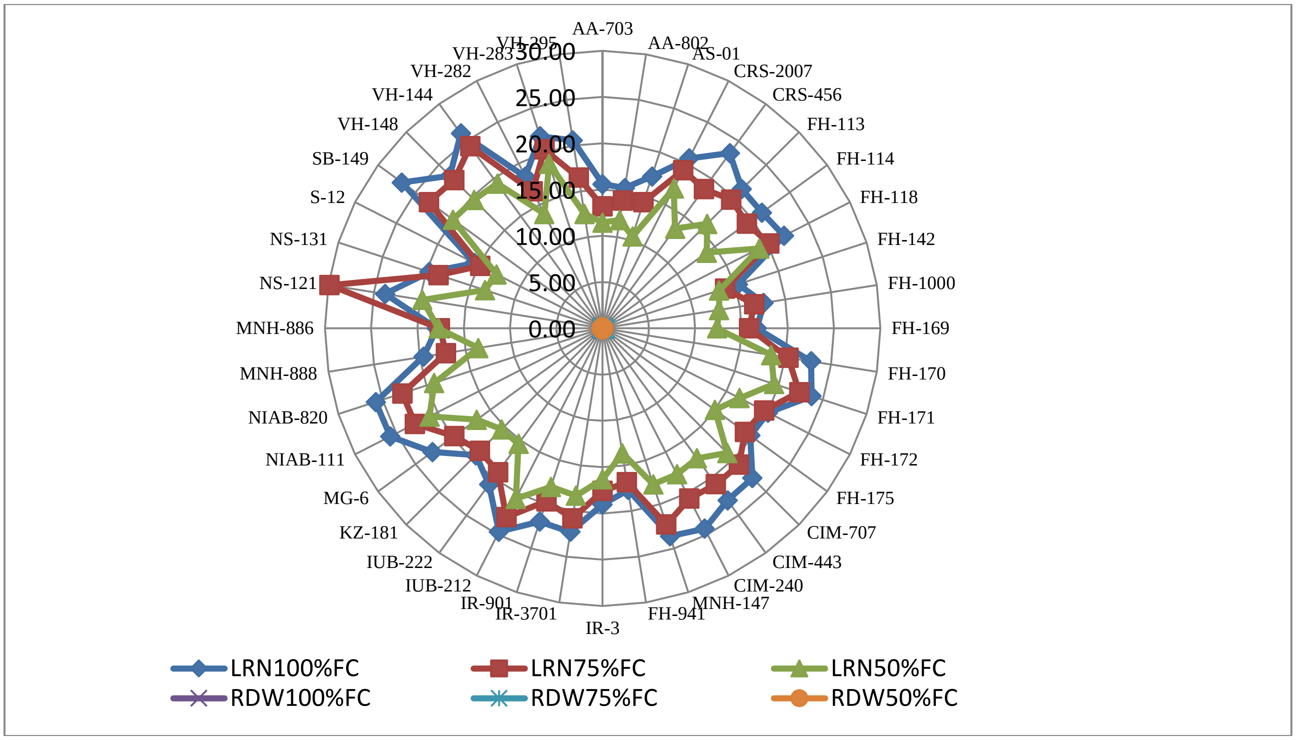

Figure 4: **Behaviors of lateral root numbers and root dry weight of 40 cotton accessions under 100%FC, 75%FC, and 50%FC. RWC = Relative water content, FC = Field capacity.**

Correlation coefficient among seedling traits

The findings revealed significant positive associations of shoot length with various parameters such as biomass, shoot fresh weight, shoot dry weight, relative water content, root dry weight, and lateral root number (as shown in Table 4). This implies that an increase in shoot length corresponds to an augmentation in biomass, shoot fresh weight, shoot dry weight, relative water content, root dry weight, and lateral root number. Root length also exhibited noteworthy positive correlations with biomass, shoot dry weight, root fresh weight, root dry weight, and relative water content. However, a noteworthy negative association was observed between root length and excised leaf water loss, indicating that an increase in root length corresponds to higher evapotranspiration.

Lateral roots demonstrated a significant positive relationship with shoot length and water content in leaves. Biomass exhibited significant and positive correlations with root length, water content(Sezener et al. 2015) in leaves, water loss from excised leaves, shoot length, shoot fresh weight, and shoot dry weight. The documented associations of leaf area with parameters related to evapotranspiration underscore the well-established relationships in this context. Relative water content (RWC) emerges as a crucial parameter for gauging water status in plant leaves. The preference for RWC as a key indicator of plant water status due to genetic variation is substantiated by the close connection between relative water content and yield under water stress conditions. Reports suggest that drought-tolerant species mitigate water loss by reducing leaf area and constraining stomatal opening(Soumya et al. 2023).

Conclusion

The study conducted on various cotton genotypes under different moisture conditions provided valuable insights into their performance and adaptability to water stress. The genotypes demonstrated diverse responses in terms of biomass, shoot and root characteristics, lateral root development, and excised leaf water loss under at all moisture levels of 100%FC, 75%FC and 50% field capacities (FC). The study findings indicate that NIAB-111, VH-144, IUB-212, MNH-886, VH-295, IR-3701, AA-802, NS-121, FH-113, and FH-142 demonstrated superior performance and were identified as drought-tolerant genotypes across all examined moisture levels. In contrast, IR-3, CIM-443, FH-1000, MNH-147, S-12, and VH-148 exhibited poor performance and were categorized as drought-sensitive genotypes in the study. The results highlight the complexity of genotype responses to water stress, emphasizing the importance of selecting appropriate cotton varieties for specific environmental conditions. The study contributes valuable information for breeding programs aimed at developing drought-tolerant cotton varieties, crucial for sustainable agriculture in the face of changing climatic conditions. Understanding the relationships between various traits and their responses to water stress provides a foundation for developing strategies to enhance cotton resilience and productivity under challenging environmental conditions.

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