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Somashekhargouda Patil
Central Coffee Research
Institute, Coffee Research
Station Post, Chikkamagaluru
District, Karnataka, India

BC Patil
Professor, Department of Crop
Physiology, University of
Agricultural sciences,
Dharwad, Karnataka, India

Corresponding Author:
Somashekhargouda Patil
Central Coffee Research
Institute, Coffee Research
Station Post, Chikkamagaluru
District, Karnataka, India

Evaluation of drought tolerance in cotton (*Gossypium hirsutum* L.) genotypes under irrigated and rainfed conditions

Somashekhargouda Patil and BC Patil

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Abstract

Drought stress is a critical constraint to cotton (*Gossypium hirsutum* L.) productivity, particularly in rainfed cultivation areas. This study assessed the drought tolerance of twenty cotton genotypes under irrigated and rainfed conditions during the 2006-2007 growing season. The trial was conducted using a randomized complete block design (RCBD) with three replications. Morphological, physiological, and yield-related traits were measured, including plant height, boll number, boll weight, seed cotton yield, relative water content (RWC), and total dry matter. Drought tolerance was further quantified using stress indices: Drought Susceptibility Index (DSI), Yield Stability Ratio (YSR), and Plant Height Stress Index (PHSI). Results showed significant genotypic variation under water-limited conditions. The average yield reduction under drought was 13.37%, with GSHV-99/291, GK-147, SSB-5, and ARB-815 demonstrating superior performance through minimal yield loss, stable RWC, and favorable stress indices. In contrast, PH-1009, KH-138, and LRA-5166 were more susceptible to drought, exhibiting greater reductions in yield and physiological parameters. Heatmap analysis effectively grouped genotypes based on multivariate trait responses, aiding the visual classification of drought-tolerant and susceptible lines. These findings highlight the potential of specific genotypes for deployment in drought-prone areas and their use in breeding programs aimed at improving cotton resilience under limited water availability.

Keywords: *Gossypium hirsutum*, drought stress, yield stability, relative water content, drought susceptibility index, genotype screening, rainfed cotton

Introduction

Cotton (*Gossypium hirsutum* L.) is a globally significant cash crop valued for its fiber, oil, and seed by-products. It contributes substantially to the agricultural economy, particularly in arid and semi-arid regions. However, the crop is increasingly vulnerable to abiotic stresses, especially drought, which has emerged as a major constraint on productivity in rainfed ecosystems (Tuteja *et al.*, 2007; Reddy *et al.*, 2017) [16, 15]. Inadequate and erratic rainfall patterns during the crop growth period adversely affect key physiological and reproductive processes, leading to substantial yield losses.

Drought stress influences cotton at various growth stages, reducing photosynthetic efficiency, altering leaf water potential, and impairing reproductive success by decreasing boll retention and seed filling (Karam *et al.*, 2006; Basal *et al.*, 2009) [14, 10]. The extent of these effects varies depending on the intensity and timing of water deficit as well as genotypic adaptability. Thus, breeding for drought resilience in cotton is a pressing need in the context of climate change and increasing water scarcity.

Effective drought screening requires a multi-trait approach, combining morphological, physiological, and yield-based parameters. Traits such as relative water content (RWC), plant height, boll number, dry matter accumulation, and yield under stress are commonly used indicators (Blum, 2011) [11]. Furthermore, stress indices like the Drought Susceptibility Index (DSI) and Yield Stability Ratio (YSR) provide quantitative assessments of genotype performance across environments (Fischer & Maurer, 1978) [13]. Advanced visualization tools such as heatmaps and biplots also facilitate the interpretation of complex, multivariate data sets in genotype evaluation (Fernandez, 1992) [12].

In this study, twenty cotton genotypes were evaluated under irrigated and rainfed conditions to identify lines with enhanced drought tolerance. The objectives were to (i) assess genotypic variability in morphological and physiological traits under drought, (ii) determine yield stability through stress indices, and (iii) identify superior genotypes suitable for drought-prone environments and breeding programs.

Material and Methods

1. Experimental Site and Design

The study was conducted under field conditions using a Randomized Complete Block Design (RCBD) with three replications at University of Agricultural Sciences, Dharwad. Two moisture regimes were imposed irrigated and rainfed. Each genotype was sown in 4-row plots (6 m length), with 75 cm row and 30 cm plant spacing. Standard agronomic practices were followed uniformly across treatments.

2. Plant Material

Twenty cotton genotypes of diverse genetic backgrounds were evaluated *viz.*, ARB-815, Sahana, ARB-757, SSB-5, CPD-755, HAG-811, ARB-760, CSH-7106, LRA-5166, NH-615, CPD-814, GBHV-184, PH-1009, GK-147, KH-138, GSHV-99/307, GSHV-99/291, KH-134, LH-1968, and LH-1995.

3. Data Collection

Observations were recorded on phenology (Days to 50% squaring, flowering, and boll opening), Growth (Plant height at 105, 120, and 170 DAS), Yield attributes (Number of bolls per plant, boll weight, and seed cotton yield), Physiology (Relative Water Content (RWC) at 95, 132, and 160 DAS), Biomass (Total dry matter accumulation at harvest) by following standard protocol. Three indices were calculated Plant Height Stress Index (PHSI), Yield Stability Ratio (YSR) and Drought Susceptibility Index (DSI).

4. Statistical Analysis

Data were analyzed using ANOVA and means were compared at the 5% level. A heatmap of key drought traits was generated using Python (Seaborn library) for visual clustering of genotypes based on performance.

Result and Discussion

1. Yield and Yield Components

The seed cotton yield significantly decreased under rainfed conditions compared to irrigated conditions, with a mean reduction of 13.37% across genotypes (Table 1). The most drought-tolerant genotype based on yield reduction was GSHV-99/291, showing a minimal decline of 0.64%, while PH-1009 experienced the greatest reduction (35.83%), indicating susceptibility to moisture stress. Under irrigation, the highest yield was recorded in ARB-815 (1564 kg/ha), followed by Sahana and ARB-757, while under rainfed conditions, ARB-815 maintained superior yield levels (1382 kg/ha), demonstrating both high productivity and stability.

The number of bolls per plant and boll weight followed similar trends. Drought conditions caused a 16.16% reduction in boll number and 5.51% reduction in boll weight. SSB-5 and CSH-7106 exhibited minimal reductions in these traits, showing resilience in maintaining reproductive components under stress. These observations suggest that genotypes maintaining higher boll number and

boll weight under water deficit are better adapted to drought, aligning with findings by Singh *et al.* (2007) ^[7], who emphasized yield component stability under stress as a critical drought-tolerance indicator.

2. Phenological Traits

The onset of key phenological stages, including 50% squaring, flowering, and boll opening, was influenced by moisture availability (Table 2). On average, flowering occurred 3 days earlier and boll opening 1 day earlier under rainfed conditions. Such early phenology is commonly observed in stress-adaptive genotypes employing a drought escape strategy. Genotypes like Sahana, ARB-757, and CPD-814 showed earlier flowering and boll opening, whereas ARB-760 and HAG-811 exhibited delayed flowering. Delay under rainfed conditions may be attributed to reduced metabolic activity under drought stress, consistent with Reddy *et al.* (2004) ^[6].

3. Plant Growth (Height)

Plant height declined under rainfed conditions at all observed stages (105, 120, and 170 DAS), with the highest reduction (11.91%) at 105 DAS (Table 3). The maximum decline at early stages may indicate sensitivity to moisture stress during vegetative growth. Genotypes CPD-755, SSB-5, and KH-138 experienced substantial reductions (>20%) in height at early stages, while LH-1968 and HAG-811 maintained plant height with minimal reductions (<5%). This suggests better early vigor and growth maintenance under limited water availability in the latter genotypes.

4. Total Dry Matter Accumulation

Drought stress significantly affected biomass accumulation (Table 4). The average reduction in total dry matter (TDM) was 25.6%, with NH-615 and GSHV-99/307 showing reductions over 40%, indicating poor biomass productivity under stress. In contrast, CPD-814 and Sahana maintained higher TDM, suggesting efficient photosynthetic activity and better water use efficiency. The capacity to accumulate biomass under limited water supply is critical for yield potential, especially under rainfed agriculture, as emphasized by Turner *et al.* (2001) ^[8].

5. Relative Water Content (RWC)

RWC, a key physiological indicator of plant water status, showed consistent reductions under rainfed conditions (Table 5). The mean reduction was 9.4% at 95 DAS, 7.0% at 132 DAS, and 3.2% at 160 DAS, showing a declining trend as plants matured. Genotypes GK-147, ARB-815, and GBHV-184 maintained high RWC under stress, suggesting efficient osmotic adjustment or deeper rooting systems. In contrast, NH-615, LH-1968, and CSH-7106 had significant drops, especially at early stages, reflecting their vulnerability. These patterns are consistent with Blum (2011) ^[11], who stated that higher RWC under drought is often associated with better cellular hydration and drought tolerance.

6. Drought Indices

Three drought screening indices were calculated Plant Height Stress Index (PHSI), Yield Stability Ratio (YSR), and Drought Susceptibility Index (DSI) (Table 6). DSI values < 1 indicate drought tolerance. The most tolerant genotypes were GSHV-99/291 (DSI=0.05), GK-147 (0.24), and SSB-5 (0.28), which combined yield stability and

minimal drought sensitivity. Conversely, PH-1009, LRA-5166, and KH-138 exhibited high DSI values (>1.7), suggesting poor adaptability. The YSR and PHSI values also supported these rankings, further validating genotype classification.

The biplot (Fig. 1) illustrates the clustering of genotypes based on yield and DSI. This visual differentiation confirms that genotypes with low DSI and high yield performance under rainfed conditions are ideal for selection and breeding.

7. Heatmap Analysis of Drought Tolerance Traits: The heatmap effectively identified drought-resilient and drought-sensitive cotton genotypes based on a combination of morphological, physiological, and yield-related traits. It highlighted that GSHV-99/291, GK-147, ARB-815 and SSB-5 are consistently tolerant and suitable for breeding efforts aimed at improving drought resilience. These insights complement trait-specific analyses and reinforce the value of integrated screening approaches in crop stress physiology.

Table 1: Yield and yield components in cotton genotypes under irrigation and rainfed condition

Sl. no	Genotypes	Yield (kg/ha)			No. of bolls/plant			Boll wt. (g/boll)		
		Irr	Rf	% redn.	Irr	Rf	% redn.	Irr	Rf	% redn.
1	ARB-815	1564	1382	13.17	18.80	14.86	20.96	3.69	3.66	0.81
2	Sahana	1459	1214	20.18	10.66	10.60	0.56	3.86	3.35	13.21
3	ARB-757	1413	1203	17.46	11.20	10.00	10.71	3.75	3.63	3.20
4	SSB-5	1364	1319	3.41	10.80	10.40	3.70	3.90	3.65	6.41
5	CPD-755	1263	1119	12.87	10.80	7.70	28.70	3.93	3.63	7.63
6	HAG-811	1200	1022	17.42	9.26	8.26	10.80	3.71	3.88	4.58
7	ARB-760	1121	1018	10.12	9.00	7.05	21.67	4.10	3.63	11.46
8	CSH-7106	1075	1038	3.56	10.40	10.26	1.35	3.48	3.45	0.86
9	LRA-5166	1051	800	31.38	7.86	6.80	13.49	3.61	3.78	4.71
10	NH-615	1047	891	17.51	9.40	9.26	1.49	3.93	3.88	1.27
11	CPD-814	1044	941	10.95	7.46	6.80	8.85	4.20	4.46	6.19
12	GBHV-184	1004	907	10.69	8.66	7.00	19.17	3.65	3.75	2.74
13	PH-1009	997	734	35.83	9.53	8.33	12.59	3.81	3.71	2.62
14	GK-147	996	967	3.00	9.93	7.60	23.46	4.40	4.31	2.05
15	KH-138	991	780	27.05	9.40	6.80	27.66	3.83	3.73	2.61
16	GSHV-99/307	949	845	12.31	9.80	7.13	27.24	3.40	3.71	9.12
17	GSHV-99/291	941	935	0.64	10.93	7.63	30.19	2.85	3.33	6.84
18	KH-134	897	836	7.30	9.66	9.33	3.42	3.33	2.851	14.41
19	LH-1968	883	868	1.73	7.93	5.46	31.15	4.08	4.00	1.96
20	LH-1995	844	761	10.91	9.00	6.66	26.00	3.91	4.20	7.42
Mean		1105	979	13.37	10.02	8.40	16.16	3.77	3.73	5.51
SEm ±		87.86	93.67		0.69	1.15		0.17	0.16	
CD @ 5%		251.60	268.23		1.99	3.31		0.49	0.46	
CV %		14.36	15.76		13.70	21.47		7.91	7.28	

Irr= Irrigated, Rf= Rainfed

Table 2: Number of days to different phenological stages in cotton genotypes under irrigated and rainfed condition

Sl. no.	Genotypes	Days for 50%								
		Squaring			Flowering			Boll opening		
		Irr	Rf	Early/ Delay	(Irr)	(Rf)	Early/ Delay	(Irr)	(Rf)	Earl/ Delay
1	ARB-815	66	66	0	92	87	3	148	152	-3
2	Sahana	69	64	5	83	82	1	148	152	-4
3	ARB-757	65	64	1	93	89	4	156	151	4
4	SSB-5	65	65	0	86	87	-1	154	153	1
5	CPD-755	67	65	2	88	88	0	156	153	3
6	HAG-811	63	64	-1	85	88	-3	149	153	4
7	ARB-760	66	66	0	91	84	7	153	151	2
8	CSH-7106	66	66	0	85	84	1	149	148	1
9	LRA-5166	64	67	2	90	87	3	154	148	6
10	NH-615	64	64	0	92	89	3	158	154	4
11	CPD-814	65	63	3	91	88	2	150	154	-4
12	GBHV-184	68	69	-1	88	86	2	151	146	5
13	PH-1009	64	64	0	89	84	5	148	148	0
14	GK-147	66	66	0	93	87	6	152	150	2
15	KH-138	66	66	0	91	87	4	155	154	1
16	GSHV-99/307	68	67	1	92	88	4	155	152	3
17	GSHV-99/291	65	64	1	87	85	2	153	153	0
18	KH-134	65	63	2	88	85	3	147	149	-2
19	LH-1968	63	63	0	91	85	6	149	150	-1
20	LH-1995	66	66	0	89	89	0	154	151	3
Mean		65	65	1	89	86	3	152	151	1
SEm ±		0.638	0.746		0.83	1.003		1.00	0.831	
CD @ 5%		1.827	2.135		2.377	2.871		2.864	2.38	
CV %		1.69	1.98		1.66	1.94		1.14	0.95	

Irr= Irrigated, Rf= Rainfed, -= delay, +=Early with reference to irrigated

Table 3: Plant height (cm) in cotton genotypes under rainfed and irrigated condition at different days

Sl. no.	Genotypes	Plant height (cm)								
		105 DAS			120 DAS			170 DAS		
		Irr	Rf	% redn.	Irr	Rf	% redn.	Irr	Rf	% redn.
1	ARB-815	80.7	69.7	15.8	117.3	112.8	4.0	112.7	110.9	1.6
2	Sahana	71.7	65.3	9.8	98.3	95.5	2.9	106.7	103.3	3.2
3	ARB-757	76.7	63.5	20.8	111.3	111.0	0.3	109.3	109.0	0.3
4	SSB-5	65.3	54.4	20.1	105.4	94.3	11.8	107.8	95.7	12.7
5	CPD-755	81.7	65.7	24.4	118.0	106.6	10.7	111.0	108.9	2.0
6	HAG-811	67.3	65.3	3.1	117.7	109.3	7.7	105.0	104.5	0.4
7	ARB-760	78.0	67.8	15.0	119.0	115.1	3.4	127.0	116.1	9.4
8	CSH-7106	75.0	67.6	10.9	97.7	94.1	3.8	115.0	114.3	0.6
9	LRA-5166	67.0	63.1	6.2	111.0	99.6	11.4	109.3	107.1	2.1
10	NH-615	64.0	53.5	19.7	95.0	89.4	6.3	113.0	105.3	7.4
11	CPD-814	73.3	64.3	14.0	112.7	102.5	10.0	112.7	111.9	0.7
12	GBHV-184	73.0	66.5	9.7	120.3	104.3	15.3	113.7	103.5	9.8
13	PH-1009	66.0	57.3	15.1	104.7	93.9	11.4	111.0	105.7	5.1
14	GK-147	71.0	66.9	6.1	111.1	100.2	10.9	113.0	106.9	5.7
15	KH-138	67.0	60.5	10.7	117.0	91.7	27.6	119.0	102.9	15.7
16	GSHV-99/307	72.7	66.3	9.7	109.0	97.9	11.3	116.0	106.5	9.0
17	GSHV-99/291	70.7	63.6	11.1	104.0	100.6	3.4	109.3	102.5	6.6
18	KH-134	68.9	66.3	3.9	107.0	102.1	4.8	111.7	93.7	19.2
19	LH-1968	70.0	69.3	1.1	112.3	110.8	1.4	117.3	106.7	9.9
20	LH-1995	73.7	66.4	10.9	106.6	106.0	0.6	119.0	114.0	4.4
Mean		71.68	64.16	11.91	109.8	101.9	7.9	113.0	106.5	6.3
SEm $\pm$		2.830	2.692		4.967	5.541		3.671	4.046	
CD @ 5%		8.103	7.709		14.224	15.866		10.511	11.586	
CV %		7.62	6.52		8.40	8.79		5.86	6.36	

Irr= Irrigated, Rf= Rainfed

Table 4: Total dry mater (gm) accumulation in cotton genotypes under irrigated and rainfed condition at harvest

Sl. no.	Genotypes	At harvest		
		Irr	Rf	% redn.
1	ARB-815	58.3	50.7	13.4
2	Sahana	67.5	59.4	12.0
3	ARB-757	67.5	55.7	17.5
4	SSB-5	57.5	49.3	14.3
5	CPD-755	56.5	48.1	14.9
6	HAG-811	59.4	46.6	21.5
7	ARB-760	62.5	40.8	34.7
8	CSH-7106	60.2	46.4	22.9
9	LRA-5166	65.1	48.0	26.3
10	NH-615	65.0	35.6	45.2
11	CPD-814	45.5	42.6	6.4
12	GBHV-184	70.4	47.8	32.1
13	PH-1009	71.2	56.1	21.2
14	GK-147	71.3	58.9	17.4
15	KH-138	71.4	49.1	31.2
16	GSHV-99/307	92.4	51.3	44.5
17	GSHV-99/291	68.8	42.1	38.8
18	KH-134	89.9	56.9	36.7
19	LH-1968	57.9	38.7	33.2
20	LH-1995	78.2	49.7	36.4
Mean		65.7	47.8	25.6
		3.04	6.41	
		8.72	18.36	
		8.31	19.8	

Irr= Irrigated, Rf= Rainfed

Table 5: Relative water content in cotton genotypes under irrigated & rainfed condition

Sl. No.	Genotypes	Relative water content (%)								
		95 DAS			132 DAS			160 DAS		
		Irr	Rf	% Redn.	Irr	Rf	% Redn.	Irr	Rf	% Redn.
1	ARB-815	81.0	77.0	5.2	86.4	80.9	6.7	79.2	79.2	0.0
2	Sahana	84.3	79.8	5.6	82.3	62.7	31.3	81.1	77.1	5.1
3	ARB-757	82.3	75.9	8.4	86.0	75.3	14.2	79.7	74.3	7.3
4	SSB-5	86.0	79.2	7.9	75.5	74.9	0.7	78.2	74.1	5.5
5	CPD-755	85.7	77.5	10.6	83.1	77.5	7.2	79.4	75.2	5.6
6	HAG-811	87.9	81.0	7.9	90.7	83.6	8.5	79.6	78.2	1.8
7	ARB-760	89.0	80.5	10.6	82.2	76.7	7.2	77.0	75.6	1.9
8	CSH-7106	88.1	75.6	16.4	77.9	71.2	9.5	81.0	80.1	1.1
9	LRA-5166	86.9	77.7	11.8	80.0	77.5	3.2	78.4	75.6	3.7
10	NH-615	85.8	73.9	16.0	86.0	80.4	7.0	78.8	75.3	4.6
11	CPD-814	88.0	79.0	10.2	80.9	78.5	3.1	78.9	73.8	6.9
12	GBHV-184	86.4	82.4	4.8	80.2	78.8	1.8	74.7	73.2	2.0
13	PH-1009	84.0	78.9	6.4	81.3	79.6	2.1	76.8	75.6	1.6
14	GK-147	78.4	78.2	0.3	83.4	77.2	8.0	81.9	81.8	0.1
15	KH-138	88.3	81.4	8.6	79.7	76.9	3.6	75.9	73.2	3.7
16	GSHV-99/307	76.6	64.6	18.7	80.6	79.3	1.7	74.0	72.4	2.1
17	GSHV-99/291	87.2	79.3	10.0	82.3	77.0	6.9	78.8	75.8	4.0
18	KH-134	85.1	77.0	9.5	84.2	74.9	12.4	79.2	78.5	0.9
19	LH-1968	87.6	71.3	15.5	82.9	80.6	2.9	81.1	77.2	5.1
20	LH-1995	84.4	81.3	3.8	81.6	79.8	2.3	79.2	78.3	1.1
Mean		84.9	77.5	9.4	82.4	77.2	7.0	78.6	76.2	3.2
SEm+-		4.21	2.34		3.38	6.44		1.75	2.022	
CD at 5%		12.051	6.71		NS	NS		5.00	NS	
CV (%)		8.65	5.18		7.25	14.23		3.93	4.50	

Irr= Irrigated, Rf= Rainfed

Table 6: Screening indices in cotton genotypes for drought conditions

Sl. no.	Genotypes	Plant Height Stress Index (PHSI)	Yield Stability Ratio (YS)	Drought Susceptibility Index (DSI)
1	ARB-815	101.6	0.88	0.98
2	Sahana	97.5	0.83	1.41
3	ARB-757	100.3	0.85	1.25
4	SSB-5	88.7	0.97	0.28
5	CPD-755	102.0	0.89	0.96
6	HAG-811	100.4	0.85	1.24
7	ARB-760	109.4	0.91	0.77
8	CSH-7106	98.7	0.97	0.29
9	LRA-5166	102.1	0.76	2.00
10	NH-615	118.6	0.85	1.25
11	CPD-814	99.8	0.90	0.83
12	GBHV-184	91.3	0.90	0.81
13	PH-1009	105.1	0.74	2.21
14	GK-147	105.7	0.97	0.24
15	KH-138	122.9	0.79	1.79
16	GSHV-99/307	109.0	0.89	0.92
17	GSHV-99/291	106.6	0.99	0.05
18	KH-134	83.9	0.93	0.57
19	LH-1968	90.3	0.98	0.14
20	LH-1995	104.4	0.90	0.82
Mean		101.9	0.89	0.94

Irr= Irrigated, Rf= Rainfed

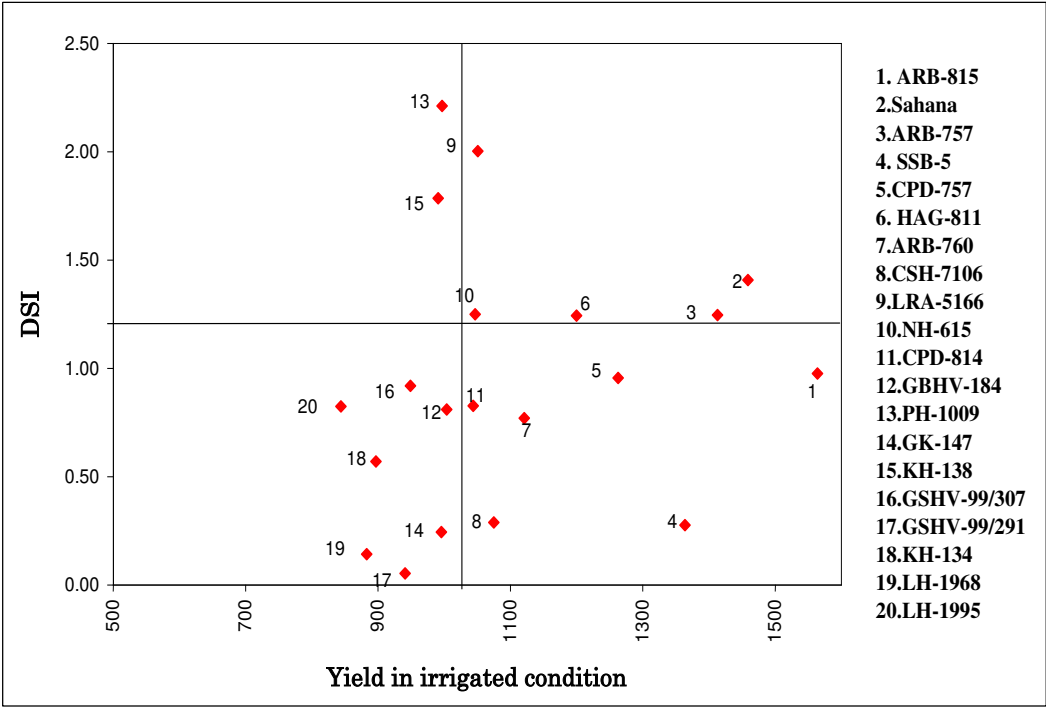


Fig 1: Biplot of seed cotton yield vs DSI of cotton genotypes

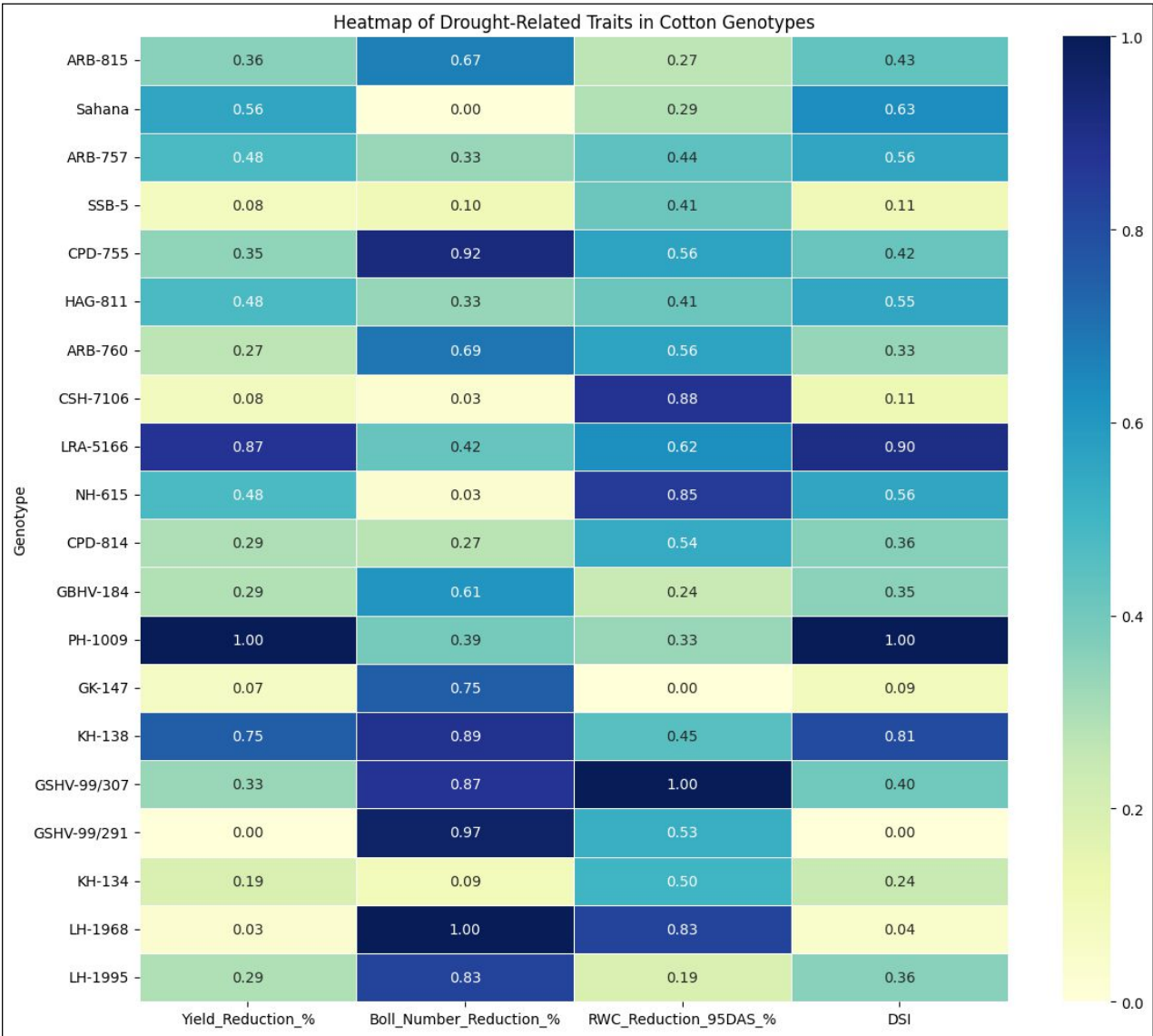


Fig 2: Heatmap showing normalized drought-related traits across twenty cotton genotypes under rainfed conditions

Conclusion

The present study evaluated twenty cotton genotypes under irrigated and rainfed conditions to identify drought-tolerant lines based on their morphological, physiological, and agronomic performance. The genotypes exhibited substantial variation in their responses to moisture stress, confirming the presence of exploitable genetic diversity for drought resilience. Genotypes such as GSHV-99/291, GK-147, SSB-5 and ARB-815 consistently outperformed others across key drought tolerance traits. These included low yield reduction, stable boll production, high relative water content (RWC), and favorable drought susceptibility index (DSI) values. In contrast, genotypes like PH-1009, KH-138 and LRA-5166 were highly susceptible to drought stress, as evidenced by severe reductions in yield, biomass, and physiological water status. Early flowering and boll opening observed in several tolerant genotypes suggest that drought escape may be an important adaptive strategy. Furthermore, genotypes with high dry matter accumulation and stable plant height demonstrated better maintenance of growth and productivity under limited water availability.

The integration of stress indices with multivariate heatmap analysis proved effective in classifying genotypes based on their overall drought performance. The identified drought-tolerant genotypes offer valuable resources for breeding programs targeting water-limited cotton-growing regions. Their incorporation into hybridization programs and further evaluation under multi-environment trials is recommended to develop cultivars with enhanced resilience and yield stability under climatic variability.

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