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**Evaluation of Genetic Parameters and Combining Ability for Drought  
Tolerance in Cotton (*Gossypium hirsutum*)**

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**Abstract**

Global climate change especially water shortage and heat waves have drastically reduced cotton production. It is necessary to develop climate resistant coupled with high yielder cotton varieties suitable for various environments. For this purpose, ten cotton varieties with different morphological, yield parameters, and drought tolerance/susceptibility were selected and hybridized using line  $\times$  tester mating design. To study the inheritance pattern, twenty-five combinations along with their parents were grown in the field following augmented design with two different treatments i-e normal and water-deficit. Under stress environment, the GCA variance ( $\sigma^2_{gca}$ ) was higher than the SCA variance ( $\sigma^2_{sca}$ ) for CLCuD, number of bolls, boll weight, seed index, fiber length, and micronaire value that shows additive type of gene action of investigated traits. Line L5 (VH-327), tester T5 (FH-Lalazar) and crosses 18 (L4  $\times$  T3) and cross 21 (L5  $\times$  T1) performed best for yield and yield contributing traits under water deficit condition environment. Cross 18 (L4  $\times$  T3), 21 (L5  $\times$  T1) and 22 (L5  $\times$  T2) had the higher SCA for the bolls number and cotton yield (15-20% higher from parents) both under normal and water deficit condition. Both under normal and water deficit condition, the best-performing genotypes and combinations (15 to 20% increase in seed cotton yield) may be used in the cotton breeding program to enhance the seed cotton yield and drought tolerance.

**Keywords:** Hybridization, GCA effects, SCA effects, drought, cotton

## Introduction

Global climate change due to frequent and intense weather conditions, has led to the occurrence of abiotic and biotic stressors which have a detrimental impact on plant growth, yield and quality (Zafar et al. 2022). Abiotic stresses, specifically, impede the physiological and metabolic activities of plants at different growth stages. Both human activities and climatic factors such as heat, drought, humidity and erratic rainfall patterns have influenced crop productivity (Zhu et al. 2023). Cotton (*Gossypium* spp.) is an important crop that is grown commercially in China, USA, India, Pakistan, Brazil, Australia and Uzbekistan for its fiber, fuel and feed making (Kashif et al. 2023). Probably, cotton covers more than 33 million hectares of land in more than 100 countries and fulfills the 31% demand for fiber all over the world (Ijaz et al. 2024). Cotton contributes almost 0.8% of GDP along with 5.5% of agricultural value addition and is cultivated in the Southern region of Punjab and some districts of the Sindh province (Mahmood et al. 2021).

At different plant developmental and reproduction phases, water shortage and high day and night temperatures have vulnerable effects on cotton plants which emphasizes the crucial importance for developing drought-tolerant cultivars. During the year, 2021, about 35% loss in cotton production was reported in Pakistan due to water deficit condition. Deficiency in irrigation water has negative effects on morphological, physiological and biochemical processes at different growth stages and results in yield reduction (Bozorov et al. 2018). A rise in both maximum and minimum temperatures gives rise to water evaporation and results in salt stress that induces water shortage/availability to the plants (Saleem et al. 2021). At the cell level, water deficit

condition resulted in a higher concentration of reactive oxygen species (ROS) that lead to oxidative stress due to the rupture of the cell membrane (Jans et al. 2021). Further, it causes a reduction in cell division, leaf surface area, metabolic adaptation, root and stem cell proliferation. These mechanisms resulted in limited access to resources and ultimately inhibited plant growth and reproduction. Even at the boll development stage, water deficiency for a short period could result in maximum loss in seed cotton yield (Naz et al. 2022). It has also been reported that prolonged exposure to water deficit condition lowers plant growth and productivity and ultimately causes plant death (Ullah et al. 2019). Management practices such as more irrigation might be used to control the water deficit condition but in the current situation, there is a dire need to boost the cotton yield potential through the development of drought-resistant varieties with limited water resources (Rehman et al. 2022).

To overcome this problem, various techniques have been used to develop climate-resilient cotton germplasm for effective and long-lasting solutions (Rahman et al. 2020). Exploitation of genetic variability in existing germplasm and screening based on morpho-physiological and biochemical characters could lead to the development of cotton genotypes with significant tolerance against abiotic stresses (Farooq et al. 2023). For plant breeders, combining ability estimates are an important factor that can help to achieve the desired targets through hybridization and selection schemes. As reported, for the selection of desired parents, combining ability techniques has been best utilized (Liaquat et al. 2023). Significant genetic variability and heterosis are the main components of a successful breeding program. Parent genotypes could be identified from the F<sub>1</sub> population through selection and then their performance-based evaluation. For selection, estimation of combining ability and possible gene action of parental lines,

Line  $\times$  tester analysis, proved to be the wisely adopted method in different breeding programs (Ammar et al. 2023). It not only provides the estimation of specific combining (SCA) and general combining ability (GCA) but also the major genetic components.

In the current study, line  $\times$  tester mating design was utilized for the hybridization of different cotton genotypes with contrasting traits to investigate the inheritance pattern and enhance the drought tolerance and seed cotton yield. The main objectives of this study were to develop the breeding material of cotton, undertaking the morphological traits contributing to drought tolerance and inheritance pattern and association in different combinations under different water level conditions.

## Materials and Methods

### 2.1 Plant material and design of experimental

Ten commercial cotton varieties were selected for hybridization purposes. Line  $\times$  tester mating design *viz* five lines and five testers was employed, and 25 crosses were developed (Kempthorne, 1957). The characteristics of the parent varieties along with passport information is presented in Table 01. The experimental was conducted at Cotton Research Institute Multan (30°08'55" N, 71°26'30" E) during the cotton growing season 2022-23. The material was sown following augmented design under normal (irrigation was applied at 8-10 days intervals till 165 days after sowing) and water deficit conditions (one irrigation was skipped compared to Normal, after the seedling establishment). Weather parameters including maximum and minimum temperature (°C), rainfall (mm), and relative humidity (%), were recorded using the

automatic weather station with data logger CRI000X (Campbell Scientific Inc., UT, USA) installed at ~750 m distance from the experimental area.

## 2.2 Data recording for investigated traits

Cotton leaf curl disease (CLCuD) was scored for ten plants (avoiding border plants) per replication (30 plants per entry) following the severity grade 0 (Asymptomatic), 1 (slight thickening of primary veins), 2 (secondary and tertiary veins thickening), 3 (vein thickening, enation or leaf curling or both), 4 (stunting of growth along with leaf enation and curling). The disease index (%) was calculated according to the formula by Liaqat et al. (2023).

**Disease index** = (Sum of all disease ratings/ total plants) × (100/maximum grade)

Plant height (PH; cm), and yield components including number of bolls (NB), boll weight (BW; g), seed index (SI; g), ginning out turn (GOT; %), seed cotton yield (SCY; g), and quality traits related to fiber i.e., fiber length (FL; cm), strength of fiber (FS; g/tax), micronaire (Mic;  $\mu\text{g}/\text{inch}$ ) were recorded. Seed index was computed by counting the one hundred seeds, followed by weighing using analytical weight balance. Fiber quality traits were recorded using Uster High Volume Instrumnet Spectrum I (Uster Technologies AG (HQ), Switzerland).

**Table I: Passport of lines and testers used for hybridization**

Lines	Varieties	Characteristics
1	VH-259	Tall, low input, medium boll size.
2	VH-282	Compact plant growth, early maturing, long staple length (>30mm)
3	VH-363	Heat tolerant, single stem, short stature, early maturing.

4	VH-369	Tall, broad leaf, late maturing
5	VH-327	High tolerant against sucking insect/pests, CLCuD and lodging tolerant, creamy pollen.
<b>Tester</b>		
1	MNH-886	Compact plant shape, early maturing,
2	MNH-814	Tall, Bold boll size, spreading growth habit
3	MNH-I016	Tall, semi-compact, low input, good boll opening.
4	FH-142	Bold boll size, high yielder, CLCuD tolerant.
5	FH-Lalazar	Heat tolerant, spreading growth habit, big boll size.

### 2.3 Statistical analysis

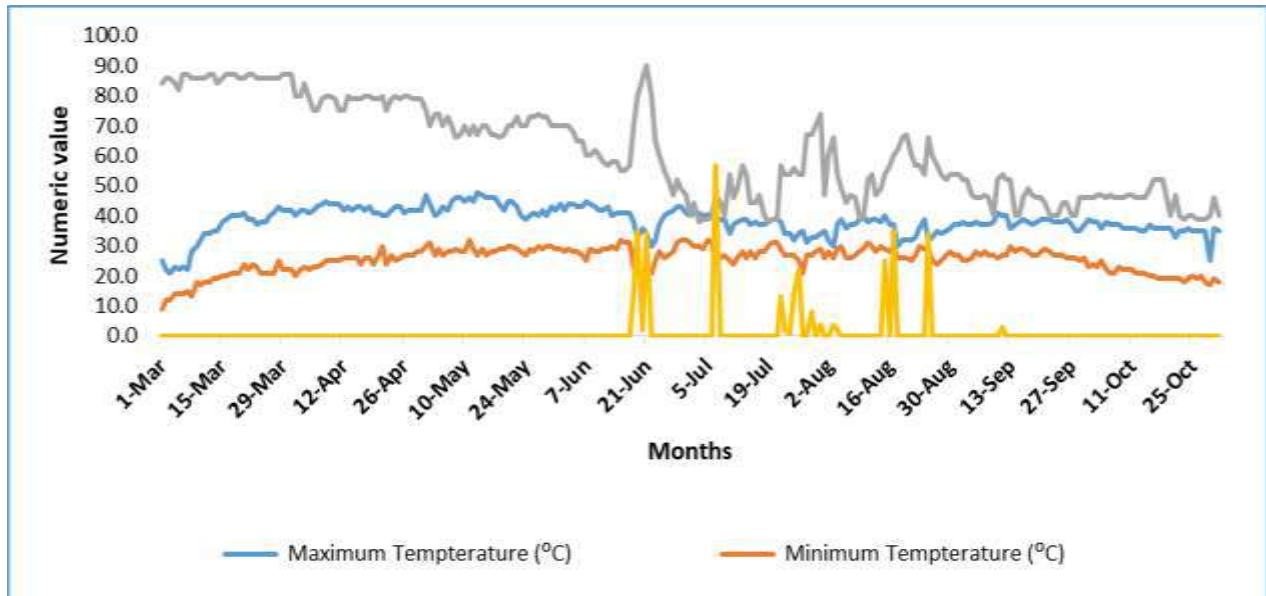
Variability among lines, testers and FI hybrids was estimated through analysis of variance using package “agricolea” at a significance level  $P < 0.05$  (Mendiburu and de Mendiburu, 2019). Genotype-trait-environment (GGE) biplot was used to evaluate the performance of genotypes under normal and stress conditions. For the estimation of genetic components and combining ability, line  $\times$  tester analysis was performed. All the statistics were performed using R software version 3.6.3.

## Results

### 3.1 Weather conditions

Temperature, rainfall, and humidity are important parameters while studying drought tolerance. During cotton growing season, range of maximum temperature was recorded from 21°C to 48°C while range for minimum was 9°C to 32°C. Maximum rainfall was observed during July i.e. 57 mm (Figure 1). Maximum temperature (48°C)

was recorded during May, while high humidity (up to 90%) was observed during June due to continuous rainfall ( $\sim 30$  mm).



**Figure 1:** Daily average weather parameters during cotton growing season, 2022-23.

### 3.2 Evaluation of parents and $F_1$ material

#### 3.2.1 Analysis of variance

Sufficient variations among treatments, parents vs crosses, parents, crosses, and their interaction were observed for all the traits under observation (Table 2) except few non-significant trends. For instance, lines showed non-significant differences for boll weight, and testers varied non-significantly for PH, GOT, FL, and Mic, under normal conditions. While under water deficit conditions, all sources of variations varied significantly (Table 3).

**Table 2:** Sum of squares for morphological and quality related traits of ten parents and 25  $F_1$  crosses under normal condition.

Source	D F	CLCu D	PH	NB	BW	SC Y	SI	GO T	FL	FS	Mic.
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Source	D F	CLCu D	PH	NB	BW	SC Y	SI	GO T	FL	FS	Mic.
Rep. (R)	02	205.9 N.S	1.50 N.S	1.48 N.S	8.49 N.S	5.15 N.S	122. 2 N.S	1.48 N.S	1.48 N.S	1.48 N.S	3.88 N.S
Trt. (T)	34	728.3 *	1.30 *	1.37 *	1.64 *	6.18 *	2.46*	5.99 *	3.61*	5.52 *	0.30*
Parents (P)	09	517.2 *	1.47 *	3.89 *	1.44 *	3.39 *	3.11*	9.62 *	2.68*	7.44 *	0.31*
Crosses (C)	24	812.4 *	1.29 *	1.76 *	1.47 *	6.82 *	2.06*	4.87 *	3.91*	5.03 *	0.30*
P vs C	01	612.7 *	5.86 *	9.52 *	7.68 *	1.59 *	5.97*	2.75 *	5.04*	1.61 *	0.25*
Lines (L)	04	1233.2 *	2.48 *	4.19 *	0.78 N.S	2.42 *	6.78*	1.45 *	1.12*	1.58 *	0.60*
Tester (T)	04	1400.2 *	7.09 N.S	1.72 *	2.86 *	7.09 *	1.02*	1.86 N.S	1.39 N.S	9.35 *	0.11 N.S
L × T	16	560.2 *	1.14 *	1.16 *	1.30 *	2.40 *	1.15*	3.20 *	2.71*	1.25 *	0.27*
Error	68	0.22	8.82	9.10	0.01	2.48	0.04	9.10	9.10	9.10	0.04

\*= Significant at  $p \leq 0.05$ , N.S = Non-significant

Table 3: Sum of squares for morphological, yield, and fiber traits of ten parents and 25  $F_1$  crosses under water deficit condition.

Source	D F	CLCu D	PH	NB	BW	SCY	SI	GO T	FL	FS	Mic.
Rep. (R)	02	236.7 N.S	195. 8 N.S	195. 8 N.S	5.60 N.S	112. 1 N.S	8.15 N.S	272. 1 N.S	172. 1 N.S	138. 6 N.S	9.72 N.S

Trt. (T)	34	589.0*	639.8*	109.6*	0.59*	112.7*	0.71*	2.66*	2.61*	26.7*	0.10*
Parents (P)	09	558.8*	612.1*	973.4*	0.52*	670.9*	0.88*	3.31*	2.62*	22.6*	0.06*
Crosses (C)	24	549.5*	675.4*	968.5*	0.68*	989.0*	0.70*	3.01*	4.05*	29.04*	0.15*
P vs C	01	180.7*	33.8*	528.1*	0.79*	855.1*	0.47*	11.1*	44.1*	8.53*	0.86*
Lines (L)	04	117.3*	582.1*	940.4*	0.81*	184.3*	1.39*	9.85*	17.8*	31.6*	0.49*
Tester (T)	04	260.0*	124.6*	305.7*	2.86*	188.8*	1.38*	5.49*	6.91*	13.09*	0.17*
L × T	16	143.7*	611.5*	453.3.2.3 1*	0.10*	551.5*	0.36*	0.67*	0.65*	2.91*	0.07*
Error	68	20.5	12.2	11.04	0.36	17.8	0.80	2.65	2.28	7.64	0.11

\*= Significant  $p \leq 0.05$ , N.S = Non-significant

### 3.2.2. Estimates of genetic components, heritability and mid parent heterosis

Under normal conditions, the GCA was less than SCA variance of all traits that represent the non-additive type of gene action under normal water condition. Also, the ratio for GCA variance to SCA variance was lower than 1, indicating higher contribution of dominance genetic variance (Table 4). Comparatively, under water deficit condition condition, the values of GCA variance for CLCuD index, NB, BW, SI, FL, and mic. were observed higher than the SCA variance, representing the influence of additive type of gene action for these traits under water deficit environment (Table 5). Ratio of the GCA variance to SCA variance was lower than 1 for all the studied traits except

micronaire value. Broad sense heritability ( $H^2$ ) and narrow sense heritability ( $h^2$ ) showed a significant variation among the two different environments (Table 4 & 5). Under normal condition, BW had maximum (0.99) while FS possessed minimum (0.77)  $H^2$  value. In case of  $h^2$ , BW, PH and FS had maximum value with 0.75, 0.74 and 0.64, respectively. Under water deficit condition, FS (0.88) and BW (0.79) possessed maximum  $H^2$  value while in terms of  $h^2$ , BW had maximum value of 0.79 also.

**Table 4: Genetic components of the morphological, yield and fiber traits under normal condition.**

Genetic components	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
Cov. H.S. (lines)	44.8	89.4	202.4	-0.03	145.7	0.37	0.75	0.56	9.7	0.02
Cov. H.S. (tester)	56.0	-28.8	372.1	0.10	313.1	-0.008	-0.08	-0.08	5.40	-0.01
Cov. H.S. (average)	6.3	3.78	149.5	0.04	110.6	0.02	0.04	0.02	0.94	0.07
Cov. F.S. (average)	354.7	481.9	786.5	0.54	375.1	0.97	2.18	1.69	29.3	0.10
$\sigma^2$ gca	6.3	3.75	149.6	0.04	110.6	0.02	0.04	0.025	0.9	0.005
$\sigma^2$ sca	186.6	380.8	385.8	0.42	800.6	0.36	1.06	0.90	4.1	0.08
$\sigma^2$ gca / $\sigma^2$ sca	0.03	0.009	0.38	0.09	0.13	0.05	0.03	0.02	0.21	0.06
F=0 Additive genetic variance	25.2	15.1	589.1	0.01	442.5	0.09	0.16	0.11	3.7	0.02

Genetic components	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
F=I Additive genetic variance	12.6	7.5	299.2	0.08	221.2	0.04	0.08	0.05	1.8	0.01
F=0 Variance due to dominance	373.3	761.7	775.9	0.85	160.1	0.73	2.12	1.80	8.3	0.17
F=I Variance due to dominance	186.6	380.8	385.8	0.42	800.6	0.36	1.06	0.90	4.1	0.08
H <sup>2</sup>	0.99	0.84	0.97	0.99	0.89	0.91	0.95	0.94	0.77	0.99
h <sup>2</sup>	0.21	0.74	0.24	0.75	0.53	0.33	0.24	0.21	0.64	0.61

**Table 5: Genetic components of the morphological, yield and fiber traits under water deficit condition.**

Genetic Components	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
Cov <sup>H.S.</sup> (lines)	-1.75	-1.95	32.4	0.04	860.9	0.07	0.61	1.14	1.01	0.02
Cov <sup>H.S.</sup> (tester)	164.0	27.5	173.6	0.18	888.7	0.06	0.32	0.41	8.53	0.06
Cov <sup>H.S.</sup> (average)	10.1	1.59	12.8	0.01	109.3	0.008	0.05	0.09	0.65	0.02
Cov <sup>F.S.</sup> (average)	182.6	-162.2	126.4	0.29	-119.5	0.08	0.89	2.05	15.8	0.04

$\sigma^2$ gca	10.1	1.595	12.85	0.01	109.35	0.005	0.055	0.095	0.65	0.02
$\sigma^2$ sca	-87.9	204.9	-217.2	-0.08	411.1	-0.14	0.65	-0.54	1.57	0.01
$\sigma^2$ gca/ $\sigma^2$ sca	-0.11	0.07	-0.05	-0.12	0.26	-0.03	0.08	-0.17	0.41	2.0
F=0 Additive genetic variance	40.5	6.39	51.5	0.05	437.4	0.03	0.23	0.39	2.61	0.08
F=I Additive genetic variance	20.2	3.19	25.7	0.02	218.7	0.01	0.11	0.19	1.30	0.04
F=0 Variance due to dominance	175.8	-409.8	-434.1	-0.17	-822.3	-0.29	-1.31	-1.08	-3.15	-0.03
F=I Variance due to dominance	-87.9	-204.9	-217.2	-0.08	-411.1	-0.14	-0.65	-0.54	-1.57	-0.01
H <sup>2</sup>	0.73	0.28	0.59	0.79	0.63	0.51	0.52	0.71	0.88	0.20
h <sup>2</sup>	0.73	0.18	0.50	0.79	0.48	0.40	0.47	0.45	0.64	0.20

CLCuD; Cotton leaf curl disease (%), PH; Plant height (cm), NB; Number of bolls, BW; Boll weight (g), SCY; Seed cotton yield (g), SI; Seed index (g), GOT; Ginning out turn (%), FL; Fiber length (cm), Fiber strength (g/tax), Mic; Micronaire ( $\mu\text{g}/\text{inch}$ ),  $\sigma^2$  GCA, GCA variance;  $\sigma^2$  SCA, SCA variance; H<sup>2</sup>, broad heritability; h<sup>2</sup>, narrow heritability

### 3.2.3 Estimates of GCA of parents

GCA effects both under both conditions i.e., the normal & water deficit, have been presented in the Table 7 and 8, respectively. CLCuD had negative and lower values for L5 under normal conditions, L2 under water deficit conditions, and T5, T3 in both conditions. Under normal conditions, L5 had higher and positive GCA effects for NB, SCY, FL, and FS, while L4 for PH, BW, and GOT. Comparatively, T5 showed positive and higher GCA effects for boll weight, GOT%, fiber length, strength, T3 for the SCY, T4 had higher GCA for mic (Table 6). Under water deficit condition, L2 had highest positive GCA values for the NB, SCY, and SI, L5 for the BW, GOT, FL, and mic. Among testers, T5 showed significantly positive GCA for BW, SI, FL, and FS, and T3 for NB and SCY (Table 7).

**Table 6: General combining ability estimates for lines and tester under normal condition.**

GCA Effects	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
	<b>Lines</b>									
<b>L1</b>	8.59	-0.6	-41.1	-0.11	-130.1	-0.38	-0.01	-1.1	-1.08	0.19
<b>L2</b>	3.59	-7.6	-23.7	0.12	-45.1	1.17	-1.5	0.3	-4.3	<b>0.19</b>
<b>L3</b>	3.54	-16.5	-27.1	-0.30	-88.4	-0.35	0.5	-0.6	-0.9	-0.01
<b>L4</b>	-0.60	<b>15.4</b>	1.4	<b>0.29</b>	92.5	-0.39	<b>1.05</b>	0.5	2.4	-0.11
<b>L5</b>	<b>-15.13</b>	9.5	<b>90.5</b>	-0.01	<b>171.2</b>	-0.05	-0.02	<b>0.8</b>	<b>3.9</b>	-0.27

GCA Effects	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
S.E.	0.12	0.02	0.03	0.03	0.04	0.04	0.02	0.03	0.02	0.01
<b>Testers</b>										
T1	0.71	-1.6	<b>47.6</b>	- 0.30	4.2	0.17	-0.20	- 0.31	-2.2	-0.07
T2	-0.42	-7.6	-18.2	- 0.08	-28.8	- 0.06	0.10	- 0.01	-2.8	-0.03
T3	-6.42	<b>9.4</b>	23.4	- 0.38	<b>117.2</b>	- 0.26	-0.42	- 0.05	0.2	-0.05
T4	15.57	4.4	-21.2	0.05	-40.8	- 0.20	0.001	- 0.11	2.2	<b>0.14</b>
T5	<b>-9.42</b>	-4.6	-31.6	<b>0.71</b>	-51.8	0.35	<b>0.52</b>	<b>0.50</b>	<b>2.5</b>	0.02
S.E.	0.12	0.02	0.02	0.03	0.03	0.05	0.02	0.02	0.02	0.02

Table 7: General combining ability estimates for lines and tester under water deficit condition.

GCA Effects	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
<b>Lines</b>										
L1	2.29	<b>10.6</b>	-2.5	- 0.07	-7.3	-0.24	-0.03	0.18	- 0.10	0.05
L2	<b>-3.97</b>	-2.5	<b>9.3</b>	0.02	<b>37.1</b>	<b>0.39</b>	-0.17	0.40	1.27	-0.08
L3	3.02	-4.9	-10.5	- 0.38	-53.4	-0.3	-0.91	- 1.60	-2.4	-0.14

GCA Effects	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
L4	-0.97	-3.1	-2.4	0.18	-1.2	0.11	-0.19	- 0.35	<b>0.64</b>	-0.11
L5	-0.37	0.04	6.2	<b>0.19</b>	24.9	0.10	<b>1.31</b>	<b>1.36</b>	0.63	<b>0.29</b>
S.E.	3.2	1.3	2.5	0.15	3.4	0.20	0.42	0.30	0.71	0.08
<b>Testers</b>										
T1	4.33	-7.4	-6.66	- 0.09	-10.8	0.07	-0.30	- 0.64	-3.8	-0.07
T2	3.0	-10.1	-8.40	- 0.04	-25.1	0.07	-0.49	- 0.45	- 2.18	<b>0.06</b>
T3	-12.0	<b>8.5</b>	<b>25.02</b>	- 0.54	<b>62.1</b>	-0.29	-0.41	- 0.09	0.96	-0.07
T4	18.33	5.2	-1.46	- 0.07	-19.2	-0.28	0.25	0.09	1.80	0.14
T5	<b>-13.66</b>	3.8	-8.48	<b>0.68</b>	-6.8	<b>0.43</b>	<b>0.94</b>	<b>1.09</b>	<b>3.30</b>	-0.12
S.E.	2.7	1.2	1.8	0.15	3.3	0.20	0.35	0.30	0.56	0.08

#### 3.2.4. Specific combining ability (SCA) effects for hybrids

Under normal condition, cross L2 × T4, showed the highest positive SCA value for NB, SCY, and mic values. Cross L2 × T3 exhibited the higher SCA value for GOT while cross L2 × T5 for FS. Cross L4 × T1 had the highest negative values for CLCuD (Table 8). Under water deficit stress, L3 × T5 showed highest positive SCA values for NB, SCY, SI, and FL (Table 9). Cross L2 × T1 showed the higher SCA value for BW. Cross L3 × T4 had the higher SCA value for FS.

**Table 8: SCA estimates for lines × tester under normal condition.**

Crosses	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
L1×T1	12.28	0.6	-52.8	-0.83	-54.2	-0.71	0.12	-0.08	-3.50	-0.16
L1×T2	3.42	-8.4	15.0	0.34	28.8	0.02	0.02	-0.38	-0.66	-0.10
L1×T3	4.42	9.6	-7.6	-0.45	-92.2	-0.27	-0.16	0.25	1.47	0.21
L1×T4	-7.57	-5.4	22.0	0.50	65.8	0.46	-0.38	0.31	0.47	0.21
L1×T5	-12.57	3.6	23.4	0.44	51.8	0.50	0.40	-0.10	2.23	-0.16
L2×T1	2.28	<b>27.6</b>	-49.2	0.22	-14.2	0.52	-0.32	0.95	2.23	-0.26
L2×T2	3.42	-16.4	6.6	0.10	-21.2	-0.03	-1.62	0.75	-1.12	-0.20
L2×T3	4.42	-3.4	-7.0	-0.19	-87.2	-0.03	<b>1.50</b>	-0.004	-3.78	-0.38
L2×T4	-2.57	11.6	<b>36.6</b>	0.56	<b>150.8</b>	0.10	1.48	-0.54	0.21	<b>0.51</b>
L2×T5	-7.57	-19.4	13.0	-0.69	-28.2	-0.55	-1.04	-1.16	<b>2.47</b>	0.33
L3×T1	2.86	-33.4	-61.6	0.42	-50.2	-0.71	0.22	-0.54	-1.24	0.37
L3×T2	-1.71	-12.4	9.2	-0.89	-37.2	0.02	0.42	-0.744	0.69	0.23
L3×T3	4.28	15.6	16.6	-0.09	-3.2	-0.27	-0.56	-0.40	1.03	-0.04

Crosses	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
L3×T4	12.28	10.6	12.2	-0.13	4.8	0.06	-0.28	0.15	0.03	- 0.24
L3×T5	-17.71	19.6	23.6	0.70	85.8	0.90	0.20	1.53	- 0.50	- 0.32
L4×T1	<b>-18.71</b>	-5.4	-29.2	-0.77	48.8	<b>1.02</b>	-0.58	0.35	1.79	0.17
L4×T2	2.42	20.6	7.6	0.30	-23.2	- 0.73	-0.08	0.85	1.23	- 0.16
L4×T3	-11.57	-6.4	32.0	0.70	145.8	0.56	0.06	0.49	0.07	0.05
L4×T4	16.42	8.6	-10.4	-0.43	- 136.2	- 0.49	-1.02	-1.64	- 0.92	- 0.24
L4×T5	11.42	-17.4	0.01	0.20	-35.2	- 0.35	-0.30	-0.06	- 2.16	0.17
L5×T1	1.28	10.6	192.8	<b>0.96</b>	69.8	- 0.11	0.56	-0.68	0.73	- 0.10
L5×T2	-7.57	16.6	-38.4	0.14	52.8	0.72	1.26	-0.48	- 0.12	0.23
L5×T3	-1.57	-15.4	-34.0	0.04	36.8	0.02	-0.72	-0.34	1.21	0.15
L5×T4	-18.57	-25.4	-60.4	-0.49	-85.2	- 0.13	-1.84	<b>1.71</b>	0.21	- 0.24
L5×T5	26.42	13.6	-60.0	-0.65	-74.2	- 0.49	0.74	-0.20	- 2.02	- 0.02
S.E.	0.27	0.05	0.05	0.06	0.57	0.12	0.05	0.05	0.04	0.03

Table 9: SCA estimates for lines × tester under water deficit condition.

Crosses	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
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Crosses	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
L1×T1	-2.0	9.80	0.01	-0.23	-19.12	0.29	-0.13	- 0.03	- 0.86	0.02
L1×T2	2.66	-4.20	-3.91	0.24	-4.85	0.15	-0.68	0.11	- 0.54	0.05
L1×T3	1.0	- 21.20	-13.6	0.11	-20.45	- 0.07	<b>0.35</b>	- 0.02	- 0.48	- 0.01
L1×T4	-7.66	18.80	4.08	-0.18	-5.78	- 0.34	0.31	- 0.30	0.54	0.03
L1×T5	6.0	-3.20	13.49	0.06	50.21	- 0.03	0.15	0.25	1.34	- 0.09
L2×T1	3.66	1.80	2.74	<b>0.33</b>	31.68	0.05	0.07	0.15	0.75	- 0.14
L2×T2	-5.0	6.13	5.81	-0.02	15.28	- 0.01	0.19	0.09	0.18	- 0.17
L2×T3	-5.0	15.80	9.12	-0.05	13.68	0.18	-0.11	0.13	0.76	- 0.04
L2×T4	3.0	- 25.86	-3.38	0.04	3.34	0.21	-0.18	0.27	- 0.73	0.10
L2×T5	3.33	2.13	- 14.30	-0.30	-63.98	- 0.44	0.02	- 0.65	- 0.96	<b>0.24</b>
L3×T1	5.66	-9.86	- 11.65	-0.12	-45.78	- 0.39	0.03	- 0.20	- 1.06	0.15
L3×T2	5.33	-2.20	-5.91	0.02	-14.85	0.33	-0.51	- 0.39	- 0.40	0.12
L3×T3	8.66	-14.2	-	-0.10	-57.12	-	0.15	-	-	-

Crosses	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
			16.34			0.42		0.42	0.84	0.04
L3×T4	-10.0	<b>20.80</b>	14.08	-0.04	34.21	-0.06	0.29	0.28	<b>1.42</b>	0.03
L3×T5	<b>-9.66</b>	5.46	<b>19.82</b>	0.24	<b>83.547</b>	<b>0.54</b>	0.03	<b>0.75</b>	0.88	-0.26
L4×T1	-2.0	0.13	8.34	0.01	16.347	0.40	-0.26	0.23	0.61	-0.08
L4×T2	2.66	-5.53	-0.58	-0.04	-3.387	-0.39	-0.11	0.55	0.37	-0.14
L4×T3	-7.33	19.13	13.72	0.06	51.680	0.26	0.04	0.41	0.72	0.02
L4×T4	5.66	-12.53	-8.78	0.02	-15.32	-0.07	0.37	-0.76	-1.44	0.03
L4×T5	1.0	-1.20	-12.70	-0.06	-49.32	-0.19	-0.04	-0.43	-0.27	0.17
L5×T1	-5.33	-1.86	0.53	0.007	16.88	-0.35	0.29	-0.14	0.56	0.04
L5×T2	-5.66	5.80	4.60	-0.21	7.813	-0.09	1.11	-0.36	0.38	0.14
L5×T3	2.66	0.46	7.17	-0.01	12.21	0.04	-0.43	-0.09	-0.16	0.08
L5×T4	9.0	-1.20	-5.99	0.15	-16.45	0.26	-0.80	0.51	0.20	-0.20
L5×T5	-0.66	-3.20	-6.31	0.06	-20.45	0.14	-0.16	0.08	-0.99	-0.06
S.E.	1.16	2.21	1.91	0.35	2.71	0.51	0.94	0.87	1.59	0.19

### 3.2.5 Mid parent heterosis

Mid parent heterosis of all traits under both environmental conditions was calculated and presented in Table 10 & 11, respectively. Combinations, L1 × T4 and L2 × T4, revealed the positive and highly significant heterosis for NB, BW and SCY under water deficit condition in contrast to normal condition. While, cross L3 × T4 showed positive and highly significant heterosis for NB, BW and SCY both under normal and water deficit conditions. Maximum and highly significant positive heterosis was observed for SCY in the cross L3 × T5, for NB in cross L2 × T1, for BW in L3 × T4 under water deficit environment. Under normal condition, the maximum and significant positive heterosis for FL was observed in L4 × T3, for FS in L2 × T1, for micronaire value in cross L2 × T5. All sources of variations varied significantly (Table 3) deficit condition, maximum positive and significant heterosis for FL was recorded in cross L2 × T2, for FS in cross L1 × T5, for micronaire value in combination L2 × T4.

**Table 10: Mid parent heterosis of crosses under normal condition.**

Crosses	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.	
L1 × T1	4.26**	8.80**	4.57**	-	15.44**	-14.07**	-4.42**	0.63*	-0.31**	-3.13**	-6.15**
L1 × T2	5.26**	9.80**	3.57**	-	19.44**	-17.07**	-3.42**	1.63*	-1.31**	-4.13**	-5.15**
L1 × T3	-5.88**	-5.66**	6.89**	16.21**	25**	1.52NS	1.11**	-0.53**	0.64**	-2.08**	
L1 × T4	-6.66*	8.47**	-27.84**	2.23**	-20	-3.42**	1.0**	0.8**	10.60**	3.09**	
L1 × T5	-14.2**	14.28**	10.75NS	32.18**	48.83**	0.23*	-0.12*	0.1**	11.94**	6.12**	
L2 × T1	-57.14*	1.81**	0*	26.82**	28.57**	4.72**	1.59*	-0.52**	13.66**	-2.08**	

L2 × T2	-12.5 <sup>NS</sup>	18.51 <sup>**</sup>	58.73 <sup>**</sup>	6.32 <sup>**</sup>	64.70 <sup>**</sup>	16.93 <sup>**</sup>	1.44 <sup>*</sup>	5.66 <sup>**</sup>	-0.78 <sup>**</sup>	-	3.22 <sup>NS</sup>		
L2 × T3	0 <sup>NS</sup>	-	21.42 <sup>**</sup>	23.07 <sup>**</sup>	6.17 <sup>**</sup>	27.81 <sup>**</sup>	4.21 <sup>**</sup>	2.21 <sup>**</sup>	6.83 <sup>**</sup>	-	15.38 <sup>**</sup>	0 <sup>**</sup>	
L2 × T4	0 <sup>NS</sup>	-9.67 <sup>**</sup>	-6.59 <sup>**</sup>	6.32 <sup>**</sup>	11.11 <sup>**</sup>	6.01 <sup>**</sup>	6.36 <sup>**</sup>	3.30 <sup>**</sup>	-	18.84 <sup>**</sup>	-5.37 <sup>**</sup>		
L2 × T5	0 <sup>**</sup>	15.38 <sup>**</sup>	90.88 <sup>**</sup>	27.93 <sup>**</sup>	49.05 <sup>**</sup>	2.59 <sup>NS</sup>	5.60 <sup>**</sup>	0.51 <sup>**</sup>	-2.85 <sup>**</sup>	-	17.02 <sup>**</sup>		
L3 × T1	-	45.45 <sup>NS</sup>	-	24.13 <sup>**</sup>	11.86 <sup>**</sup>	-3.37 <sup>**</sup>	7.69 <sup>*</sup>	-0.50 <sup>**</sup>	-	1.15 <sup>**</sup>	-0.85 <sup>**</sup>	0.689 <sup>**</sup>	13.04 <sup>**</sup>
L3 × T2	0 <sup>NS</sup>	-25 <sup>**</sup>	-1.44 <sup>**</sup>	20 <sup>**</sup>	15.55 <sup>**</sup>	5.88 <sup>**</sup>	1.61 <sup>**</sup>	-	1.142 <sup>NS</sup>	-6.16 <sup>**</sup>	10.37 <sup>**</sup>		
L3 × T3	0 <sup>**</sup>	-16 <sup>**</sup>	9.85 <sup>**</sup>	-	16.41 <sup>**</sup>	-6.77 <sup>**</sup>	7.5 <sup>**</sup>	1.84 <sup>**</sup>	0 <sup>**</sup>	-4.41 <sup>NS</sup>	9.37 <sup>**</sup>		
L3 × T4	20 <sup>**</sup>	7.14 <sup>**</sup>	16.09 <sup>**</sup>	18.70 <sup>**</sup>	38.09 <sup>**</sup>	5.88 <sup>**</sup>	0.24 <sup>**</sup>	0.35 <sup>**</sup>	0 <sup>**</sup>	-	1.54 <sup>**</sup>		
L3 × T5	50 <sup>**</sup>	21.73 <sup>**</sup>	2.36 <sup>**</sup>	18.21 <sup>**</sup>	19.14 <sup>**</sup>	4.29 <sup>**</sup>	0.122 <sup>*</sup>	1.41 <sup>**</sup>	1.36 <sup>**</sup>	0.43 <sup>**</sup>			
L4 × T1	-	77.77 <sup>**</sup>	7.69 <sup>**</sup>	23.07 <sup>**</sup>	38.66 <sup>**</sup>	82.60 <sup>**</sup>	18.56 <sup>**</sup>	0.84 <sup>**</sup>	6.9 <sup>**</sup>	-2.78 <sup>**</sup>	-1.7 <sup>**</sup>		
L4 × T2	-	66.66 <sup>**</sup>	-3.22 <sup>**</sup>	50.79 <sup>**</sup>	6.45 <sup>**</sup>	130.98 <sup>**</sup>	34.2 <sup>**</sup>	0.36 <sup>**</sup>	5.4 <sup>**</sup>	4.72 <sup>**</sup>	-6 <sup>**</sup>		
L4 × T3	20 <sup>**</sup>	6.25 <sup>**</sup>	3.12 <sup>**</sup>	43.75 <sup>**</sup>	66.67 <sup>**</sup>	1.96 <sup>*</sup>	0.60 <sup>**</sup>	9.09 <sup>**</sup>	-0.68 <sup>**</sup>	-	11.11 <sup>**</sup>		
L4 × T4	-50 <sup>**</sup>	-8.57 <sup>**</sup>	26.55 <sup>**</sup>	78.70 <sup>**</sup>	25.45 <sup>NS</sup>	21.91 <sup>**</sup>	0.98 <sup>**</sup>	6.90 <sup>**</sup>	-0.64 <sup>**</sup>	-8.0 <sup>**</sup>			
L4 × T5	71.42 <sup>**</sup>	13.33 <sup>**</sup>	-32.43 <sup>**</sup>	34.22 <sup>**</sup>	-1.36 <sup>**</sup>	1.28 <sup>**</sup>	3.03 <sup>**</sup>	-1.58 <sup>**</sup>	0.63 <sup>**</sup>	-	10.89 <sup>**</sup>		
L5 × T1	71.42 <sup>**</sup>	-	18.18 <sup>**</sup>	-26.22 <sup>**</sup>	47.22 <sup>**</sup>	50 <sup>**</sup>	7.5 <sup>**</sup>	0.35 <sup>**</sup>	4.67 <sup>**</sup>	-4.94 <sup>**</sup>	-3.03 <sup>**</sup>		
L5 × T2	-60 <sup>**</sup>	12.28 <sup>**</sup>	488.40 <sup>**</sup>	28 <sup>**</sup>	94.28 <sup>**</sup>	9.20 <sup>**</sup>	0.24 <sup>**</sup>	-1.42 <sup>**</sup>	3.40 <sup>**</sup>	-3.37 <sup>**</sup>			
L5 × T3	-	84.62 <sup>**</sup>	8.47 <sup>**</sup>	55.71 <sup>**</sup>	9.09 <sup>**</sup>	71.64 <sup>**</sup>	11.76 <sup>**</sup>	1.70 <sup>**</sup>	1.027 <sup>**</sup>	-2.6 <sup>**</sup>	2.27 <sup>**</sup>		
L5 × T4	-	81.82 <sup>**</sup>	-	10.76 <sup>**</sup>	40.52 <sup>**</sup>	15.85 <sup>**</sup>	63.88 <sup>**</sup>	5.52 <sup>**</sup>	-	2.85 <sup>**</sup>	0.68 <sup>**</sup>	3.7 <sup>**</sup>	-1.12 <sup>**</sup>

L5 × T5	- 76.47**	-5.45**	15.70**	1.92**	15.88**	-1.74**	- 6.09 <sup>NS</sup>	6.7**	5**	-6.66**
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\*= Significant, \*\*= Highly Significant, N.S = Non-significant

Table II: Mid parent heterosis of crosses under water deficit condition.

Crosses	CLCuD	PH	NB	BW	SCY	SI	GOT	FL	FS	Mic.
LI × T1	3.7**	10**	27.45**	-20.58**	0 <sup>NS</sup>	-5.26**	1.84 <sup>NS</sup>	-1.15 <sup>NS</sup>	-6.1**	-5.88 <sup>NS</sup>
LI × T2	-4**	-18.18**	31.14**	8.82**	42.85**	-6.32**	1.06 <sup>NS</sup>	- 2.713**	-4.8**	6.93 <sup>NS</sup>
LI × T3	4.76**	-18.51**	-11.76**	-3.44**	-7.40**	-2.59**	3.0 <sup>NS</sup>	-1.84**	-0.95 <sup>NS</sup>	1.96 <sup>NS</sup>
LI × T4	10.34**	15.78**	36.17**	23.52**	68.75**	0.61 <sup>NS</sup>	0.18 <sup>NS</sup>	0.18 <sup>NS</sup>	4.83**	0 <sup>NS</sup>
LI × T5	-20**	-25**	11.80**	15.38**	28**	1.19**	1.29 <sup>NS</sup>	-1.8 <sup>NS</sup>	10.86**	-2.97 <sup>NS</sup>
L2 × T1	12**	-40**	88.75**	5.55**	100**	17.5**	1.25 <sup>NS</sup>	8.22**	0 <sup>NS</sup>	-7.07 <sup>NS</sup>
L2 × T2	4.34**	-59.09**	34.94**	0**	34.61**	3.0**	-5.3**	11.36**	-3.27**	- 4.081 <sup>NS</sup>
L2 × T3	- 26.31**	-25.92**	15.315**	3.22**	32.25**	7.8**	7.1**	-0.18 <sup>NS</sup>	-1.51**	-5.05 <sup>NS</sup>
L2 × T4	-11.1**	-36.84**	50.7**	13.88**	90**	-2.13**	4.00*	1.48 <sup>NS</sup>	-4**	14.85**
L2 × T5	-44.4**	-41.6**	40.77**	-7.3**	33.33**	-2.6**	-0.07 <sup>NS</sup>	-0.54 <sup>NS</sup>	3.7**	12.24**
L3 × T1	- 18.18**	-56.25**	21.495**	13.3**	53.84**	6.5**	0.37 <sup>NS</sup>	0.58**	-7.91**	13.6**

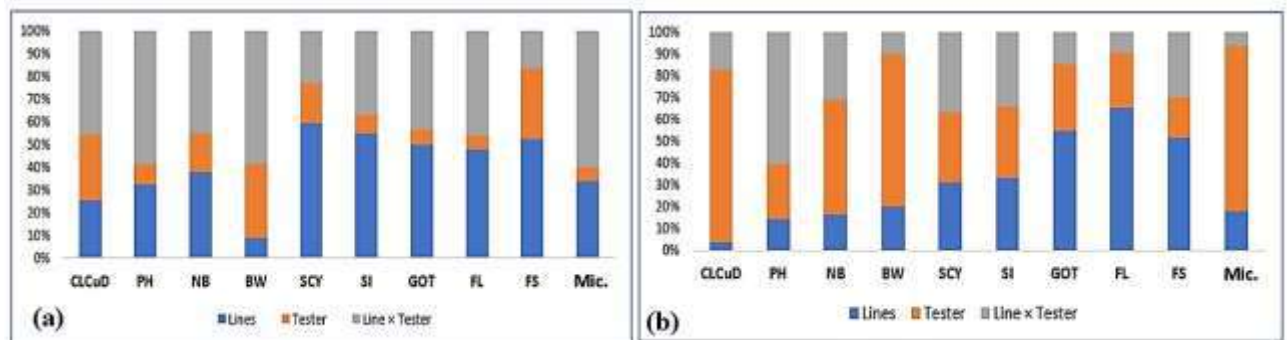
L3 × T2	20**	-22.22**	-9.44**	-13.33**	-24.05**	9.09**	1.36 <sup>NS</sup>	2.53**	-3.87**	10.63*
L3 × T3	12.5**	-4.347**	65.38**	12**	84.6**	5.0**	-0.76 <sup>NS</sup>	-2.04**	-7.9**	3.15 <sup>NS</sup>
L3 × T4	33.33**	46.66**	51.02**	16.66**	33.3**	4.054**	-0.24 <sup>NS</sup>	1.50 <sup>NS</sup>	-0.72 <sup>NS</sup>	1.03 <sup>NS</sup>
L3 × T5	-73.33**	0 <sup>NS</sup>	70.2**	34.28**	213.0**	26.79**	-0.61 <sup>NS</sup>	9.023**	-5.1**	-2.12 <sup>NS</sup>
L4 × T1	-64.70**	9.80**	44.08**	29.82**	113.7**	40.14**	0.746 <sup>NS</sup>	5.22**	-4.27**	-7.69*
L4 × T2	20**	-20**	-16.53**	36.842**	38.36**	4.89**	0.24 <sup>NS</sup>	10.90**	-3.54**	-6.79**
L4 × T3	-45.45**	-16.92**	31.60**	74.468**	128.5**	23.74**	0.882 <sup>NS</sup>	5.01**	-3.31**	-7.69 <sup>NS</sup>
L4 × T4	68.42**	22.44**	-51.14**	29.82**	-29.03**	-4.05**	0.12 <sup>NS</sup>	-2.35**	-6.57**	-11.3*
L4 × T5	100**	-18.64**	-22.22**	43.28**	52.72**	7.18**	0.48 <sup>NS</sup>	6.0**	0 <sup>NS</sup>	-4.85 <sup>NS</sup>
L5 × T1	-60**	23.404**	60.572**	23.94**	108.88**	11.6**	-0.37 <sup>NS</sup>	3.9**	-2.7**	-1.07 <sup>NS</sup>
L5 × T2	-77.7**	13.72**	56.950**	4.22**	63.17**	8.7**	0.36 <sup>NS</sup>	5.4**	-4.89**	2.17 <sup>NS</sup>
L5 × T3	-71.42**	-18.03**	46.52**	14.75**	65.51**	7.6**	-2.52 <sup>NS</sup>	1.73**	-2.74**	-1.07 <sup>NS</sup>
L5 × T4	9.090**	-2.2**	21.21**	-1.40**	19.14**	-3.03**	-6.14**	8.61**	-0.66 <sup>NS</sup>	-7.4 <sup>NS</sup>
L5 × T5	38.46**	-5.45**	21.160**	-6.17**	28.7**	-11.76**	-1.09 <sup>NS</sup>	3.44**	-5.19**	0 <sup>NS</sup>

\*= Significant, \*\*= Highly Significant, N.S = Non-significant

### 3.2.6 Proportional contribution of lines, testers, and their interactions

The proportional contribution of lines, testers and their interactions under normal and water deficit conditions have been presented in Fig. 3a & 3b. Under normal condition, lines contributed higher for the traits; SCY, SI, GOT, FL, while the contribution of crosses was higher for CLCuD, PH, BW, and mic. Under water deficit

condition, testers contributed significantly higher for CLCuD, NB, BW and mic value. Lines contributed higher towards GOT, FL, and FS. Crosses showed higher contribution to PH, SCY, and SI.

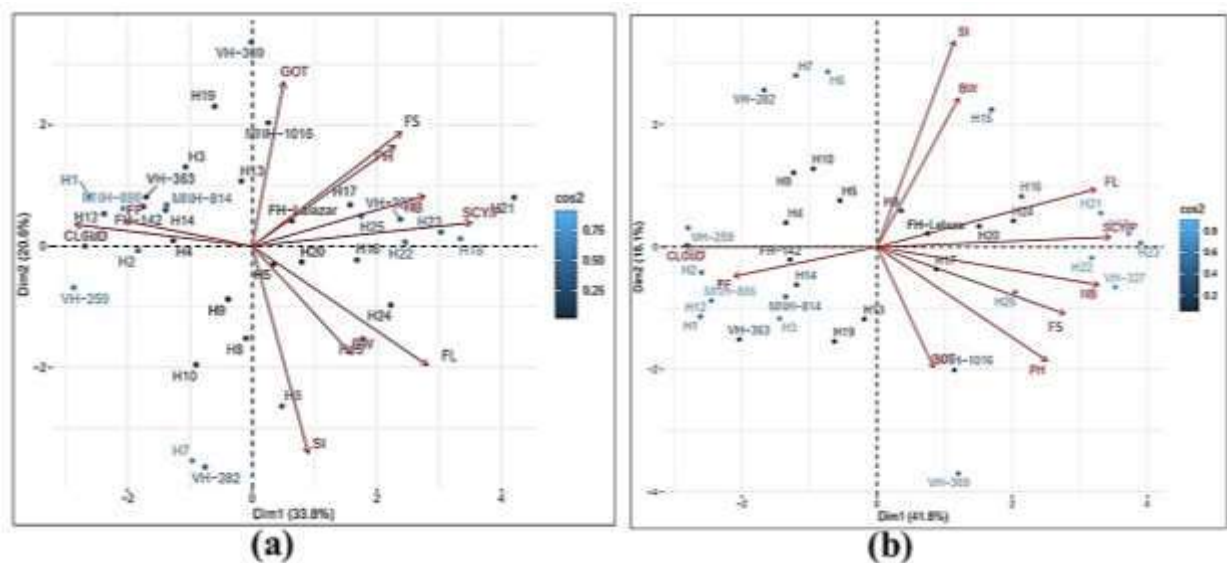


**Figure 2:** Proportional contribution of lines, testers, and their interaction (line  $\times$  tester) for the morphological, yield, and fiber quality traits under normal (a) and water deficit (b) conditions.

### 3.2.7. Performance of parents and their hybrids under normal and water deficit conditions

Under normal condition, PCI and PC2 explained 33.8% and 20.6% of the total variability, respectively (Fig. 3a). Overall, hybrids (H2I; L5  $\times$  T1, H18; L4  $\times$  T3, H23; L5  $\times$  T3) showed highest values for seed cotton yield and number of bolls under both normal and water deficit condition environments. Parents had higher values for CLCuD compared to hybrids. Cross I5 (L3  $\times$  T5) had highest boll weight, cross 6 (L2  $\times$  T1) had highest seed index. Line 5 had highest number of bolls, while T3 showed highest GOT%.

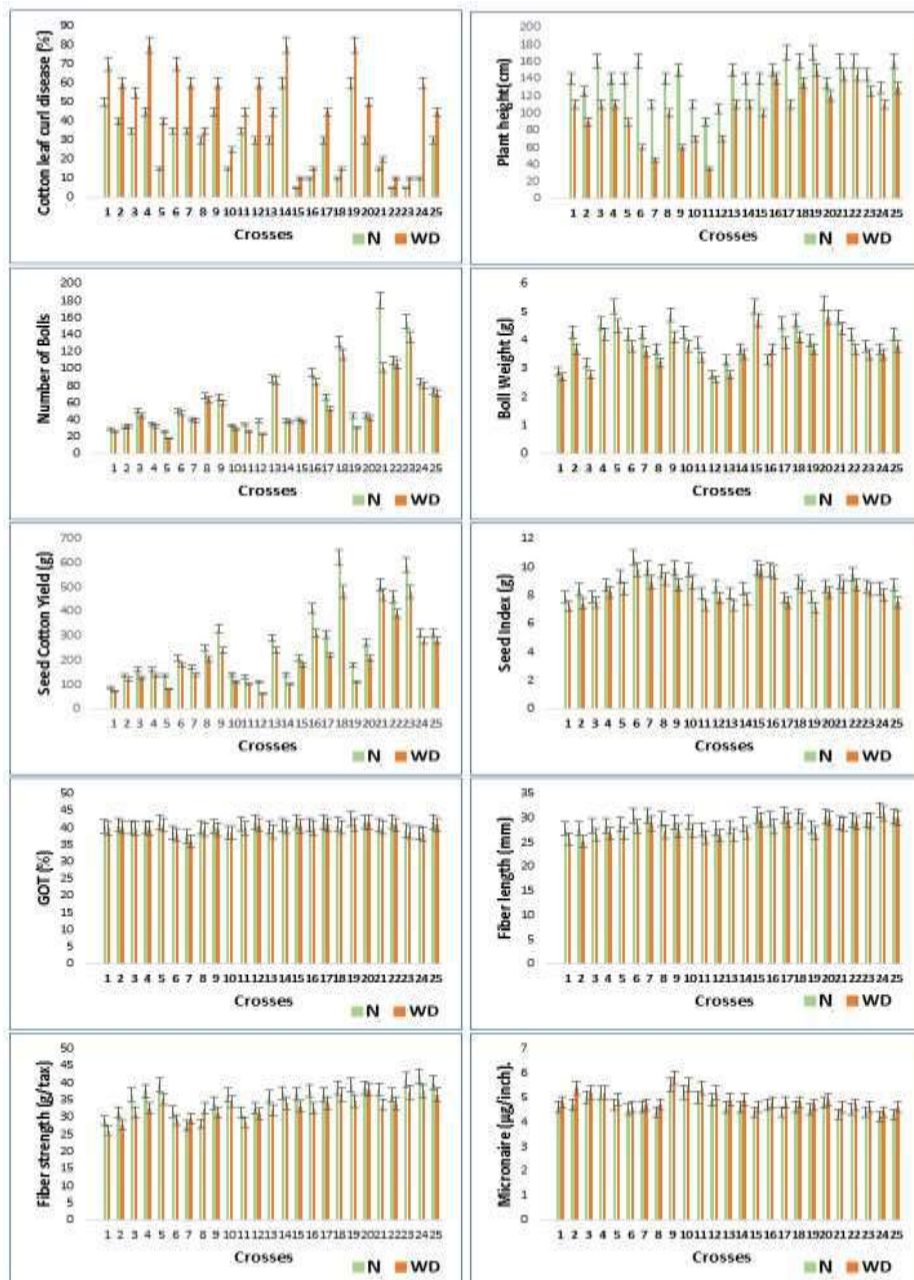
Under water deficit condition environment, PCI explained the 41.8% while PC2 18.1% of the variability (Fig. 3b). Line 5 was found at the extreme of the plot for the number of bolls. Tester, T3, was also higher for GOT% same as under normal condition.



**Figure 3:** Biplot analysis of lines, testers and hybrids for morphological, yield and fiber traits under normal (a) and water deficit (b) conditions.

### 3.2.8 Mean performance of crosses for morphological, yield and fiber traits

The data for morphological, yield and fiber parameters under both water environments were recorded. Mean data of crosses have been presented in Fig. 4. Cross 20 (L4 x T5) and 21 (L5 x T1) showed higher mean values for boll weight. Cross 15 (L3 x T5), 16 (L4 x T1) and 22 (L5 x T2) were significantly high for seed index. In case of CLCuD, fiber length, strength and micronaire value, cross 22 (L5 x T2), 23 (L5 x T3) and 24 (L5 x T4) were observed with maximum mean values both under normal and water deficit condition.



**Figure 4:** Mean performance of crosses under normal (N) and water deficit (WD) conditions.

## Discussion

Global climate change threatens cotton yield (Loka et al. 2020). A 5°C rise in temperature enhance the risk of both floods and droughts (Soong et al. 2020). Both the increasing global population and fiber demand have created a challenge to develop stress-resistant cultivars. Cotton crop is exposed to various climate-driven biotic and abiotic stresses (Haroon et al. 2023). This calls for assessment of variability and create new genetic combinations to select drought and heat tolerant germplasm for future breeding programs. This study found that the genetic variability was better manifested in hybrids as they revealed significant variations for all the traits under two different environmental conditions (Table & 3) (Kamara et al. 2021). Genetic diversity was further portioned into different components due to SCA and GCA (Griffing, 1956) which provides a better understanding of how these characters have been controlled (Imtiaz et al. 2023). SCA and GCA variances were found significant under both watered environments that revealed the contribution of additive and non-additive gene action. Earlier, in various studies, both type of gene actions have been reported in the inheritance pattern of morphological, yield, and fiber traits (Abro et al. 2009; Imran et al. 2012). It was observed that under normal irrigation condition, the GCA variance was less than the SCA variance indicating the superiority of non-additive gene action for all the traits (Table 4). Previously, the dominating role of the non-additive genes for SI, fiber quality and SCY has been reported (Zare et al. 2014; Ali et al. 2016). Non-additive gene action supports the opportunity for the selection of such genotypes or combinations for the improvement of the specific trait in a hybrid. While under water deficit condition condition, traits like CLCuD, NB, BW, SI, FL, and mic value exhibit a higher GCA variance than the SCA variance which represents the additive type of gene action (Table 5) as also supported by Javid et al. 2014. Sufficient heterosis is also needed

for any breeding programme. Crosses,  $L1 \times T4$ ,  $L2 \times T4$ ,  $L3 \times T4$ ,  $L3 \times T5$ ,  $L2 \times T1$ ,  $L3 \times T4$  were observed with with maximum heterosis for different traits under both treatments. These results are related with previous findings and may be selected to design the breeding strategy for the targeted traits (Monicashree et al. 2017; Maqbool et al. 2017; Sajjad et al. 2016).

For a successful breeding program and gene pyramiding, several crossing cycles followed by selection of good combining parents are important (Desoky et al. 2021). Among lines, L5 (VH-327), had the highest values for the NB, SCY, FL and FS both under normal and water deficit condition environments (Table 6) which indicated that this line can be used for the improvement of these traits. While, T5 (FH-Lalazar) showed higher GCA effects for BW, GOT%, FL, FS under normal while higher values for BW, SI, FL and FS under water deficit condition (Table 7). Previously, the dominant role of genes regarding the genetic mechanism for these traits has been reported (Imran et al. 2012; Shakeel et al. 2012). Specific combining ability estimates is used to identify the crosses that perform well in specific combinations for the desired trait (Liaqat et al. 2023). Under water deficit condition, cross  $L3 \times T5$ , possessed higher SCA value for NB, SCY, SI, and FL. Such crosses can produce transgressive segregants, hence giving rise to new genetic combinations and significantly improving the specific traits. Under water deficit condition, line 5 possessed a higher value for the NB, Cross 18 ( $L4 \times T3$ ) and cross 21 ( $L5 \times T1$ ) was the best performing for SCY and tester, T3, was also higher for GOT% and present on the extreme of biplot (Fig. 3b). These lines, crossed and testers revealed significant potential for morphological and yield traits under water deficit condition environment and important from breeding point of

view. Emphasis on seed number per boll (Seed index) and boll numbers could be an important criterion while breeding for drought-tolerant cotton genotypes (Ur Rehman et al. 2007).

### Conclusion

Changing climate scenario has become a serious threat to cotton yield and production. This study provides valuable insights for the genetic components underlying morphological, yield, and fiber traits of different cotton varieties and their interaction under water deficit condition. Hybridization in different combinations resulted in increased seed cotton yield and drought tolerance. General and specific combining ability estimates revealed the inheritance pattern of lines, testers and their interactions for morphological and yield traits under normal and water stress conditions. VH-327, FH-Lalazar and cross 18 (L4 x T3) and cross 21 (L5 x T1) were the best performing for yield contributing traits under water deficit condition. These lines and testers have the potential to be utilized in breeding programme specifically under water stress environment. Cross L3 × T5 possessed the higher SCA effect and may be exploited for the development of a hybrid for specific traits. Cross 18 (L4 x T3), 21 (L5 x T1), 22 (L5 x T2) and 23 (L5 x T3) exhibited the maximum seed cotton yield and number of bolls under both normal and water deficit condition that is almost 15-20% higher than the parental genotypes. Our investigation not only provides an understanding of the inheritance pattern of drought tolerance but also provides the opportunity to design the breeding strategy specifically for the drought-stress environment.

**Abbreviations:** DF; Degree of freedom, CLCuD; Cotton leaf curl disease (%), PH; Plant height (cm), NB; Number of bolls, BW; Boll weight (g), SCY; Seed cotton yield (g), SI;

Seed index (g), GOT; Ginning out turn (%), FL; Fiber length (cm), FS; Fiber strength (g/tax), Mic; Micronaire ( $\mu\text{g}/\text{inch}$ ).

## Declarations

**Conflict of interest:** We confirm that this paper has not been published anywhere.

**Ethical approval:** All the authors have no conflict of interest with any institution, journal etc.

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