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Effect of Drought Stress on Combining Ability and Heterotic Potential for Yield Components in Intra-Specific Egyptian Cotton Crosses

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ABSTRACT

Drought stress is a serious abiotic stressor affecting cotton production; therefore, the study aims to estimate both combining ability types and heterosis over better and mid-parent for yield-component traits in 10 Egyptian cotton varieties and their 21 intra-specific crosses, using the line x tester model under normal and drought stress conditions. The experiment was laid out in a randomized complete block design with three replications. The analysis of variance showed significant differences between genotypes (lines, testers, and crosses) for yield and its components. Three varieties Giza 86, Giza 96, and Giza 94 had the highest mean performance values for yield components under both conditions. Giza 92 x Giza 45 exhibited significant and useful heterosis over better parents for all the studied yield traits. On the other hand, the cotton cross Giza 70 x Giza 94 has negative and highly significant heterosis over better parents for all the studied yield traits. Non-additive effects played a relatively large role in the manifestation of these features, compared to additive effects. Broad sense heritability had higher values than narrow sense heritability for all yield traits under both conditions. Also, all traits showed higher values of two types of heritability under normal conditions than under drought conditions. Generally, cotton varieties Giza 89, Giza 94, and Giza 94 considered good combiners for all yield traits under normal and drought stress. These varieties are considered beneficial parents for breeding programs to produce new varieties characterized by high yield and the best yield traits.

Keywords: drought stress, dominance, yield components, heterosis, cotton.

INTRODUCTION

Cotton is the king of fiber crops and an important cash crop that influences economics and social affairs all over the world, also called the white gold (Sahare et al., 2022) and belongs to the species *Gossypium barbadense* L. Egyptian cotton is renowned for its high fiber quality, softness, and strength due to its long staple length, which makes it ideal for luxurious bedding, clothing, and other textiles. This exceptional cotton is grown in the Nile Delta region of Egypt, where the unique climate and fertile soil contribute to its superior qualities. The Egyptian cotton breeders improved new varieties with higher yield production coupled with high fiber quality. The environmental stress factors have a key role in the agricultural system and negatively affect the growth and productivity, such as salinity (Helaly et al., 2017; Abdelaal et al., 2020a; Al-Shammari et al., 2023, 2025), heat (El Sabagh et al., 2019; Elkelish et al., 2020; Abdelaal et al., 2021a), and drought stress (Abdelaal et al., 2018, 2020b, 2021b; AlKahtani et al., 2020, 2021; Hafez et al., 2020; Arafa et al., 2021). One of the major environmental factors that impacts 45% of global crop production is drought, which

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affects many morphological characters (Elsawy et al., 2022; Abdou et al., 2023) and physiological processes (Abdelaal et al., 2024; Abd-El-Aty et al., 2024). Egypt struggles with the lack of water needed for agriculture. Furthermore, growing cotton in recently recovered desert areas has become essential. Numerous agronomic characteristics and seed cotton production are greatly impacted by drought stress (Abdel-Monaem et al., 2018; Yehia, 2022; Yehia and El-Absy 2023). Under drought stress *G. barbadense* cotton productivity reduced by 31.44 to 42% (Yehia et al., 2023). Creating new cotton varieties that are more resilient to drought stress is the best strategy to combat drought stress (Abdelraheem et al., 2019). To select the suitable drought-tolerant parents, a successful breeding program must first assess to screening the available germplasm (Mashal et al., 2021). The various techniques like diallel, line x tester, or other mating analysis are useful instruments for identifying suitable parents and superior crossings for the traits under stress. Under drought stress both additive and dominance components were significant for all traits (Abo Sen et al., 2022; Mahdy et al., 2022a; ElFeki et al., 2024).

Line x Tester analysis in plant breeding technique is used to estimate both general and specific combining ability. It involves crossing a set of lines (female parents) with a set of testers (male parents) to assess their general and specific combining abilities for traits like yield, its components, and fiber quality. This technique helps to identify superior hybrid combinations and provides insights into the genetic mechanisms controlling traits like yield, its components, and fiber quality. By analyzing the general combining ability (GCA) of the parents and the specific combining ability (SCA) of the crosses, breeders can select suitable parents and develop improved cotton varieties (Mahdy et al., 2022b; Abdel-Aty et al., 2023). Therefore, the objective of the present study was to have an idea about the nature of general and specific combining ability for yield and its components in Egyptian cotton and to identify good combining parents and superior crosses over both mid and better parent, and to investigate genetic components under normal and drought stress.

MATERIAL AND METHODS

The experiment of the present study was carried out at Sakha Experimental Research Station, Kafr El-Sheikh Governorate, Agricultural Research Center (ARC), Egypt, (31°07’ N latitude, 30°05’ E longitude), during the two growing summer seasons of 2018 and 2019. Seven genotypes were crossed as lines with three as testers in a line-tester method to produce 21 F_1 intra-specific cotton crosses. The parental cotton genotypes belonging to *Gossypium barbadense* L. Pedigree and category of the seven lines and three testers Egyptian parental cotton varieties is presented in Table 1. The selfed seeds of the ten Egyptian cotton varieties were obtained from the Egyptian Cotton Maintenance Research Department, Cotton Research Institute (CRI), Agricultural Research Center (ARC), Egypt.

During the summer growing season of 2018, the selfed seeds of the seven lines and three testers Egyptian cotton genotypes were planted, and hybridization was performed to produce 21 F1 cotton crosses, with the lines as females and the testers as males. The 21 F_1 cotton crosses and their 10 parental genotypes (7 lines and 3 testers) were sown in a randomized complete block design with 3 replications during the 2019 growing season. Each plot consisted of three rows for each genotype (seven lines, three testers, and their 21 F_1 crosses), four meters long, 60 cm apart, and 40 cm between hills within a row. After full emergence, seedlings were thinned to one plant per hill. All agronomic practices were applied as recommended by the Ministry of Agriculture for cotton cultivation. The normal irrigation experiment was irrigated as required, while the water-stressed experiment was irrigated just before the wilting point throughout the growing season. The soil moisture percentage was determined gravimetrically on a dry basis just before irrigation.

At harvest, the individual plants of seven lines and three testers cotton varieties plus their 21 F_1 crosses were harvested to estimate six yield component traits;

1. Boll weight (BW) is the average weight of ten opening bolls per plant in grams.
2. Seed cotton yield per plant (SCY/P) is the weight of all maturely opened bolls picked from the plant in grams were weighed by using an electronic balance.
3. Lint yield per plant (LY/P) in grams, the weight of lint yield after ginning in grams using an electronic balance.
4. Lint percentage (L%) is the percentage ratio between lint yield and seed cotton yield.
5. Seed index (SI), the weight of 100-seed from each plant in grams.
6. Number of bolls/plant (NB/P) is the number of fully opening bolls per plant.

Statistical Analysis

The analysis of variance (ANOVA) and significance tests were performed on plot mean basis as outlined by Gomez and Gomez (1984). Also, mean values of parents were used to estimate heterosis relative to the mid and better parent (Fonseca and Patterson, 1968). The line x tester analysis was performed as outlined by Kempthorne (1957). Heterosis as a percentage of mid and better-parents (MP and BP) was determined according to Steel and Torrie (1980). Also, heritability in both broad (h^2b %) and narrow (h^2n %) senses was estimated (Mather, 1949; Allard, 1960).

Table 1. Pedigree and category of the seven lines and three testers of the Egyptian parental cotton varieties

No.	Parents	Pedigree	Category
Lines			
L1	Giza 70	Giza 59 x Giza 51	Extra-long staple
L2	Giza 85	Giza 67 x CB58	Long staple
L3	Giza 87	(Giza 77 x Giza 45) A	Extra-long staple
L4	Giza 92	Giza 84 x (Giza 74 x Giza 68)	Extra-long staple
L5	Giza 93	Giza 77 x S6	Extra-long staple
L6	Giza 96	Giza 84 x (Giza 70 x Giza 51b) x S62	Extra-long staple
L7	Giza 89	Giza 75 x 6022	Long staple
Testers			
T1	Giza 45	Giza 28 x Giza 7	Extra-long staple
T2	Giza 86	Giza 75 x Giza 81	Long staple
T3	Giza 94	Giza 86 x 10229	Long staple

RESULTS AND DISCUSSION

The study for combining ability was made possible since the mean squares for the genotypes of all the variables under investigation in both settings were highly significant ($P \leq 0.01$), suggesting that hybrids and their parents differed from one another (Table 2). The additive and dominant variances were calculated by dividing the entire genetic variability into general and particular combining abilities. Additionally, for every trait under study in both environments, the mean squares of the parents, crosses, parents vs. crosses, lines, testers, and lines x testers were highly significant ($P \leq 0.01$), except for testers for lint percentage under drought stress. The mean performance of lines, testers, and their interaction for all studied yield and its component traits under both normal and drought stress conditions is shown in Tables 3 and 4 for the ten parental varieties and the 21 F_1 crosses, respectively. The mean performance of the genotypes appeared to vary across the two environments with respect to their means for all the studied traits. The parental lines (Giza 93, Giza 96, and Giza 89) and the two testers (Giza 86 and Giza 94) gave the best mean performance for all the studied yield traits under both environments. Fifteen out of 21 F_1 cotton crosses showed the mean performance for all studied traits under normal and drought stress.

Table 2. Mean squares of line x tester analysis for yield components under normal (E1) and drought (E2) stress conditions

SOV	d.f.	Boll weight BW		Seed cotton yield/plant SCY/P		Lint yield/plant LY/P	
		E1	E2	E1	E2	E1	E2
Replications	2	0.01	0.01	277.48	1819.20	34.54	344.07*
Genotypes	30	0.34**	0.29**	17273.98**	8462.17**	3154.51**	1438.03**
Parents (P)	9	0.20**	0.22**	12317.37**	7930.76**	2630.76**	1471.74**
Crosses (c)	20	0.39**	0.32**	14139.98**	5618.64**	2644.61**	998.55**
P x C	1	0.76**	0.28**	124563.58*	70115.44**	18066.32**	9924.11**
Lines	6	0.35**	0.30**	19730.91**	7622.25**	3951.85**	1544.37**
Testers	2	1.53**	1.28**	63431.27**	25222.92*	11640.64*	4207.51**
Lines x testers	12	0.22**	0.17**	3129.29**	1349.45*	491.65**	190.82*
Error	60	0.01	0.01	145.87	672.64	24.05	90.19
SOV		Seed index SI		Lint percentage L%		Number of boll/plant NB/P	
		E1	E2	E1	E2	E1	E2
Replications	2	0.02	0.39**	0.04	2.92	22.69	247.28*
Genotypes	30	1.81**	1.49**	13.60**	13.09**	974.07**	652.69**
Parents (P)	9	3.19**	2.22**	24.07**	24.82**	705.16**	540.94**
Crosses (c)	20	0.98**	0.99**	8.92**	7.23*	731.13**	388.08**
P x C	1	6.20**	4.95**	13.01**	24.81**	8253.02**	6950.68**
Lines	6	0.90**	0.96**	16.52**	13.80**	962.54**	464.49**
Testers	2	5.19**	4.53**	27.93**	16.52**	2397.66**	872.53**
Lines x testers	12	0.32**	0.42**	1.95**	2.40*	337.67**	269.12**
Error	60	0.025	0.035	0.195	1.209	20.737	68.165

Table 3. Mean performances for yield components of the parental genotypes under normal (E1) and drought (E2) stress conditions

Traits	Boll weight BW		Seed cotton yield/plant SCY/P		Lint yield/plant LY/P		Seed index SI		Lint percentage L%		Number of bolls/plants NB/P	
Genotypes	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2
Lines												
Giza 70	2.94	2.68	166.85	119.89	55.56	35.34	9.8	8.8	33.3	29.3	56.83	44.85
Giza 85	2.99	2.79	246.87	195.95	90.78	68.90	10.5	9.7	36.8	35.2	82.83	70.32
Giza 87	2.95	2.70	172.39	119.22	57.85	38.23	9.9	8.9	33.6	32.1	58.39	44.23
Giza 92	2.91	2.65	164.05	119.05	54.09	37.74	8.9	8.0	33.0	31.7	56.56	45.07
Giza 93	3.06	2.90	181.83	135.33	64.39	46.68	10.1	9.3	35.4	34.4	59.50	46.75
Giza 96	3.29	3.08	251.46	204.05	96.39	74.71	10.6	9.6	38.3	36.6	76.34	66.17
Giza 89	3.34	3.12	285.89	229.37	110.77	84.69	10.7	9.9	38.7	36.9	85.58	73.51
Testers												
Giza 45	2.67	2.49	134.92	98.61	43.16	30.74	7.9	7.4	32.0	31.2	50.45	39.57
Giza 86	3.33	3.19	242.14	177.53	88.61	62.46	10.7	9.6	36.6	35.1	72.74	55.77
Giza 94	3.50	3.30	336.28	239.13	135.92	91.28	11.5	10.1	40.4	38.1	96.10	72.43
LSD at 0.05	**0.12**	**0.19**	**19.73**	**42.36**	**8.01**	**15.51**	**0.26**	**0.31**	**0.72**	**1.80**	**7.44**	**13.48**
LSD at 0.01	**0.17**	**0.26**	**26.23**	**56.33**	**10.65**	**20.63**	**0.34**	**0.41**	**0.96**	**2.39**	**9.89**	**17.93**

The high positive and significant general and specific combining ability (GCA and SCA) effects are preferable for all the studied yield and its components as presented in Tables 5 and 6. The parental varieties Giza 96 and Giza 94 (lines) and Giza 89 (tester) showed positive and highly significant GCA for all the studied traits except, Giza 89 for boll weight under both environments. While parental varieties had negative and highly significant GCA for most of the studied traits, except Giza 85 for seed cotton yield and seed index; Giza 92 for boll weight, and Giza 86 for seed cotton yield, lint yield, and lint percentage (Table 5).

Table 4. Mean performances for yield components of the Egyptian cotton crosses genotypes under normal (E1) and drought (E2) stress conditions

Traits	Boll weight BW		Seed cotton yield/plant SCY		Lint yield/plant LY		Seed index SI		Lint percentage L%		Number of bolls/plants	
Cotton crosses	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2
Giza 70 x Giza 45	2.9	2.6	219.3	177.7	74.39	57.34	9.9	8.6	33.9	32.2	75.94	68.65
Giza 70 x Giza 86	2.8	2.5	226.2	213.6	77.74	74.28	9.6	8.6	34.4	33.5	81.93	87.71
Giza 70 x Giza 94	3.2	2.9	234.2	180.2	85.85	63.56	10.5	9.9	36.7	35.2	73.05	61.35
Giza 85 x Giza 45	3.3	2.9	225.5	180.5	81.30	62.89	10.5	9.5	36.0	34.8	68.84	62.95
Giza 85 x Giza 86	3.5	3.2	311.2	225.9	117.33	83.39	10.7	9.6	37.7	36.6	88.75	70.47
Giza 85 x Giza 94	3.6	3.4	374.5	238.3	141.59	85.96	10.9	9.8	37.8	36.1	105.46	70.92
Giza 87 x Giza 45	2.7	2.6	203.1	159.1	68.82	52.95	10.3	9.5	33.9	33.3	74.57	61.72
Giza 87 x Giza 86	3.7	3.4	236.4	200.2	81.33	63.92	10.3	9.5	34.4	33.3	64.60	56.77
Giza 87 x Giza 94	3.2	2.8	343.0	253.0	128.16	90.70	11.3	10.1	37.4	35.9	107.90	91.18
Giza 92 x Giza 45	2.9	2.6	213.1	155.2	74.98	52.65	9.8	8.6	35.2	33.9	73.92	59.51
Giza 92 x Giza 86	3.4	3.1	239.8	202.2	82.15	63.29	10.1	9.3	34.3	32.5	69.82	62.03
Giza 92 x Giza 94	3.5	3.1	355.1	237.7	134.76	86.91	11.3	10.1	37.9	36.5	100.99	76.00
Giza 93 x Giza 45	2.9	2.7	240.4	182.4	86.01	62.86	10.2	9.3	35.8	34.5	83.08	68.30
Giza 93 x Giza 86	3.6	3.3	317.4	219.5	116.59	87.80	10.7	9.5	36.7	35.3	88.14	74.58
Giza 93 x Giza 94	3.5	3.2	393.5	282.5	147.20	99.47	11.6	10.3	37.4	35.2	111.14	88.94
Giza 96 x Giza 45	3.6	3.3	331.3	249.4	122.68	90.18	10.5	9.5	37.0	36.2	90.99	75.20
Giza 96 x Giza 86	3.5	3.2	352.6	255.0	138.04	94.93	10.4	9.3	39.1	37.2	101.05	79.42
Giza 96 x Giza 94	3.6	3.2	395.6	298.9	155.66	112.70	11.6	10.7	39.3	37.6	110.16	92.28
Giza 89 x Giza 45	2.5	2.4	267.5	197.0	99.20	70.26	10.4	9.6	37.1	35.7	105.49	81.68
Giza 89 x Giza 86	3.6	3.2	375.0	272.4	143.82	100.05	11.3	10.5	38.4	36.7	103.28	84.73
Giza 89 x Giza 94	3.6	3.4	373.2	293.0	143.32	106.61	11.0	10.0	38.4	36.4	104.27	87.19
LSD at 0.05	**0.12**	**0.19**	**19.73**	**42.36**	**8.01**	**15.51**	**0.26**	**0.31**	**0.72**	**1.80**	**7.44**	**13.48**
LSD at 0.01	**0.17**	**0.26**	**26.23**	**56.33**	**10.65**	**20.63**	**0.34**	**0.41**	**0.96**	**2.39**	**9.89**	**17.93**

Under normal irrigation and drought stress, the specific combining ability (SCA) effects were positive and substantial for the hybrids of two parents, or at least one parent had a positive GCA effect in the majority of cases. This suggests that both additive and non-additive gene effects govern this feature. Furthermore, several hybrids had SCA effects that were opposite to those of their respective parents. Four cotton crosses (Giza 92 x Giza 45, Giza 87 x Giza 45, Giza 93 x Giza 86, and Giza 96 x Giza 45) showed positive and non-significant SCA effect for the studied yield traits under both environments (Table 6). Four cotton crosses (Giza 70 x Giza 45, Giza 87 x Giza 86, Giza 96 x Giza 45 and Giza 89 x Giza 94), four (Giza 85 x Giza 45, Giza 92 x Giza 94, Giza 89 x Giza 86 and Giza 96 x Giza 94) and two crosses (Giza 70 x Giza 86 and Giza 87 x Giza 94) showed positive and significant or highly significant SCA effects for boll weight, seed index and number of bolls per plant under both normal and water stress conditions, respectively. On the other side, five cotton crosses (Giza 70 x Giza 86, Giza 96 x Giza 86, Giza 96 x Giza 94 and Giza 89 x Giza 45), one (Giza 70 x Giza 94), one (Giza 70 x Giza 94), one (Giza 92 x Giza 86), two (Giza 70 x Giza 94 and Giza 87 x Giza 86) and four (Giza 85 x Giza 94, Giza 92 x Giza 45, Giza 96 x Giza 86 and Giza 89 x Giza 94) had negative and significant or highly significant SCA effect under both environments conditions for boll weight, seed cotton yield, lint yield, lint percentage, number of bolls per plant and seed index, respectively (Table 6).

Table 5. General combining ability (GCA) effects of the Egyptian parental cotton genotypes under normal (E1) and drought (E2) stress conditions

Traits	Boll weight BW		Seed cotton yield/plant SCY		Lint yield/plant LY	
Genotypes	E1	E2	E1	E2	E1	E2
Lines						
Giza 70 (L1)	-0.34**	-0.32**	-69.97**	-32.03**	-30.24**	-14.12**
Giza 85 (L2)	0.15**	0.15**	7.16	-7.66	3.84*	-1.77
Giza 87 (L3)	-0.10**	-0.09*	-35.75**	-18.43*	-16.80**	-9.99**
Giza 92 (L4)	-0.01	-0.04	-27.23**	-24.21**	-12.27**	-11.56**
Giza 93 (L5)	0.06*	0.06	20.53**	5.56	7.03**	4.20
Giza 96 (L6)	0.28**	0.25**	63.26**	45.19**	29.22**	20.09**
Giza 89 (L7)	-0.04	-0.01	42.00**	31.58**	19.21**	13.13**
LSD at 0.05	**0.05**	**0.08**	**8.05**	**17.29**	**3.27**	**6.33**
LSD at 0.01	**0.07**	**0.10**	**10.71**	**23.00**	**4.35**	**8.42**
Tasters						
Giza 45 (T1)	-0.31**	-0.29**	-53.67**	-36.66**	-22.80**	-15.02**
Giza 86 (T2)	0.15**	0.14**	-2.50	4.43	-1.43	1.92
Giza 94 (T3)	0.16**	0.14**	56.16**	32.23**	24.22**	13.10**
LSD at 0.05	**0.03**	**0.05**	**5.27**	**11.32**	**2.14**	**4.15**
LSD at 0.01	**0.04**	**0.07**	**7.01**	**15.06**	**2.85**	**5.51**
Traits	Seed index SI		Lint percentage L%		Number of bolls/plant NB/P	
Genotypes	E1	E2	E1	E2	E1	E2
Lines						
Giza 70 (L1)	-0.59**	-0.58**	-1.63**	-1.53**	-12.71**	-1.79
Giza 85 (L2)	0.08	0.03	0.58**	0.68	-2.00	-6.25*
Giza 87 (L3)	0.00	0.09	-1.40**	-1.02**	-7.33**	-4.47
Giza 92 (L4)	-0.24**	-0.26**	-0.82**	-0.87*	-8.11**	-8.51**
Giza 93 (L5)	0.25**	0.09	0.03	-0.18	4.44**	2.91
Giza 96 (L6)	0.20**	0.20**	1.90**	1.83**	11.05**	7.94**
Giza 89 (L7)	0.29**	0.43**	1.34**	1.09**	14.66**	10.17**
LSD at 0.05	**0.10**	**0.13**	**0.29**	**0.73**	**3.036**	**5.505**
LSD at 0.01	**0.14**	**0.17**	**0.39**	**0.97**	**4.038**	**7.321**
Tasters						
Giza 45 (T1)	-0.39**	-0.38**	-1.05**	-0.81**	-7.85**	-6.07**
Giza 86 (T2)	-0.17**	-0.14**	-0.19	-0.14	-4.32**	-0.69
Giza 94 (T3)	0.56**	0.52**	1.24**	0.95**	12.17**	6.76**
LSD at 0.05	**0.07**	**0.08**	**0.19**	**0.48**	**1.988**	**3.604**
LSD at 0.01	**0.09**	**0.11**	**0.26**	**0.64**	**2.644**	**4.793**

Table 6. Specific combining ability (SCA) effects of the Egyptian cotton crosses under normal (E1) and drought (E2) stress conditions

Traits	Boll weight BW		Seed cotton yield/plant SCY		Lint yield/plant LY	
Genotypes	E1	E2	E1	E2	E1	E2
Giza 70 x Giza 45	0.25**	0.19**	46.40**	23.87	17.86**	7.30
Giza 70 x Giza 86	-0.34**	-0.30**	2.13	18.69	-0.16	7.30
Giza 70 x Giza 94	0.09*	0.12	-48.53**	-42.56**	-17.70**	-14.60**
Giza 85 x Giza 45	0.14**	0.00	-24.55**	2.27	-9.30**	0.49
Giza 85 x Giza 86	-0.09*	-0.07	9.96	6.60	5.35	4.06
Giza 85 x Giza 94	-0.06	0.07	14.59*	-8.87	3.96	-4.55
Giza 87 x Giza 45	-0.16**	-0.05	-4.05	-8.33	-1.15	-1.23
Giza 87 x Giza 86	0.32**	0.32**	-21.95**	-8.34	-10.01**	-7.19
Giza 87 x Giza 94	-0.17**	-0.27**	26.00**	16.67	11.17**	8.41
Giza 92 x Giza 45	-0.08	-0.07	-2.57	-6.53	0.48	0.05
Giza 92 x Giza 86	0.01	0.03	-27.05**	-0.55	-13.72**	-6.25

Giza 92 x Giza 94	0.08	0.04	29.61**	7.09	13.24**	6.20
Giza 93 x Giza 45	-0.14**	-0.11	-23.03**	-9.08	-7.79**	-5.50
Giza 93 x Giza 86	0.11*	0.12	2.78	-13.05	1.41	2.50
Giza 93 x Giza 94	0.04	-0.01	20.25**	22.13	6.38*	3.00
Giza 96 x Giza 45	0.38**	0.34**	25.18**	18.29	6.69*	5.92
Giza 96 x Giza 86	-0.24**	-0.18**	-4.76	-17.22	0.67	-6.26
Giza 96 x Giza 94	-0.15**	-0.16*	-20.42**	-1.07	-7.36*	0.34
Giza 89 x Giza 45	-0.39**	-0.30**	-17.39*	-20.47	-6.78*	-7.03
Giza 89 x Giza 86	0.23**	0.08	38.89**	13.88	16.46**	5.82
Giza 89 x Giza 94	0.16**	0.22**	-21.51**	6.59	-9.68**	1.21
LSD at 0.05	**0.09**	**0.14**	**13.95**	**29.95**	**5.66**	**10.97**
LSD at 0.01	**0.12**	**0.18**	**18.55**	**39.83**	**7.53**	**14.59**
Traits	Seed index SI		Lint percentage L%		Number of bolls/plant NB/P	
Genotypes	E1	E2	E1	E2	E1	E2
Giza 70 x Giza 45	0.29**	-0.11	-0.01	-0.60	6.82*	2.15
Giza 70 x Giza 86	-0.24*	-0.27*	-0.43	-0.01	9.27**	15.83**
Giza 70 x Giza 94	-0.05	0.38**	0.44	0.61	-16.09**	-17.98**
Giza 85 x Giza 45	0.19*	0.27*	-0.09	-0.20	-10.99**	0.91
Giza 85 x Giza 86	0.19*	0.09	0.70**	0.90	5.38*	3.05
Giza 85 x Giza 94	-0.38**	-0.36**	-0.61*	-0.70	5.61*	-3.96
Giza 87 x Giza 45	0.04	0.18	-0.29	-0.08	0.07	-2.10
Giza 87 x Giza 86	-0.15	-0.08	-0.63*	-0.68	-13.44**	-12.43*
Giza 87 x Giza 94	0.12	-0.10	0.92**	0.76	13.37**	14.53**
Giza 92 x Giza 45	-0.22*	-0.34**	0.44	0.42	0.19	-0.26
Giza 92 x Giza 86	-0.10	0.08	-1.35**	-1.63*	-7.44**	-3.13
Giza 92 x Giza 94	0.32**	0.26*	0.91**	1.21	7.25**	3.39
Giza 93 x Giza 45	-0.25**	-0.02	0.19	0.28	-3.19	-2.90
Giza 93 x Giza 86	0.03	-0.03	0.28	0.48	-1.66	-2.01
Giza 93 x Giza 94	0.22*	0.05	-0.47	-0.76	4.85	4.91
Giza 96 x Giza 45	0.06	0.09	-0.43	-0.03	-1.89	-1.03
Giza 96 x Giza 86	-0.27**	-0.41**	0.83**	0.34	4.64	-2.19
Giza 96 x Giza 94	0.21*	0.32**	-0.40	-0.31	-2.74	3.22
Giza 89 x Giza 45	-0.11	-0.08	0.18	0.21	9.00**	3.22
Giza 89 x Giza 86	0.54**	0.63**	0.60*	0.61	3.25	0.89
Giza 89 x Giza 94	-0.43**	-0.55**	-0.78**	-0.81	-12.25**	-4.11
LSD at 0.05	**0.18**	**0.22**	**0.51**	**1.27**	**5.259**	**9.535**
LSD at 0.01	**0.24**	**0.29**	**0.68**	**1.69**	**6.994**	**12.681**

For the yield components, the percentage of the F_1 mean performance from both mid-parent (MP) and better-parent (BP), represents both desirable and helpful heterosis are given in Tables 7 and 8, respectively of the 21 F_1 cotton crosses. Four cotton crosses (Giza 87 x Giza 86, Giza 92 x Giza 94, Giza 93 x Giza 86, and Giza 96 x Giza 45) were positive and highly significant over mid-parent (MP) heterosis for boll weight, seed cotton yield/plant, and lint yield/plant under both stress conditions. Also, another five cotton crosses (Giza 87 x Giza 45, Giza 92 x Giza 45, Giza 93 x Giza 45 and Giza 96 x Giza 45 and Giza 89 x Giza 45) had positive and highly significant heterosis over mid-parent (MP) for seed index, lint percentage and number of bolls/plants under normal and drought stress (Table 7). Seven cotton crosses (Giza 70 x Giza 45, Giza 87 x Giza 45, Giza 87 x Giza 94, Giza 92 x Giza 45, Giza 93 x Giza 45, Giza 89 x Giza 86 and Giza 89 x Giza 94) showed positive and highly significant heterosis over mid-parent (MP) for seed cotton yield/plant and lint yield/plant under normal and drought stress conditions. Thirteen and fifteen out of 21 F_1 cotton crosses had positive and highly significant heterosis for seed index and number of bolls/plant, respectively. Only one cotton cross (Giza 92 x Giza 45) had positive and highly significant heterosis, and another

cross (Giza 70 x Giza 45) had negative and highly significant heterosis over better-parent (BP) all the studied yield component traits under both conditions (Table 8). Four crosses (Giza 70 x Giza 45, Giza 93 x Giza 45, Giza 96 x Giza 45, and Giza 96 x Giza 86) showed positive and highly significant over better-parent (BP) for both seed cotton yield/plant and lint yield/plant.

Table 7. Heterosis (%) relative to mid-parents (MP) for of the Egyptian cotton crosses under normal (E1) and drought (E2) stress conditions

Traits	Boll weight BW		Seed cotton yield/plant SCY		Lint yield/plant LY	
Genotypes	E1	E2	E1	E1	E2	E1
Giza 70 x Giza 45	2.94	0.32	45.36**	62.68**	50.71**	73.54**
Giza 70 x Giza 86	-11.81**	-13.62**	10.63*	43.66**	7.85	51.90**
Giza 70 x Giza 94	-0.34	-1.37	-6.89*	0.38	-10.33**	0.39
Giza 85 x Giza 45	15.76**	8.77**	18.13**	22.56	21.40**	26.22
Giza 85 x Giza 86	10.99**	8.11**	27.27**	20.98*	30.80**	26.95*
Giza 85 x Giza 94	9.48**	10.43**	28.43**	9.52	24.91**	7.33
Giza 87 x Giza 45	-3.36	-0.71	32.17**	46.09**	36.26**	53.54**
Giza 87 x Giza 86	16.44**	14.73**	14.04**	34.93**	11.05*	26.97*
Giza 87 x Giza 94	-1.47	-7.03*	34.85**	41.21**	32.28**	40.07**
Giza 92 x Giza 45	3.35	1.49	42.55**	42.56*	54.20**	53.76**
Giza 92 x Giza 86	10.06**	7.33*	18.06**	36.37**	15.14**	26.32
Giza 92 x Giza 94	9.73**	5.68*	41.95**	32.70**	41.85**	34.73**
Giza 93 x Giza 45	0.99	-0.80	51.78**	55.91**	59.95**	62.39**
Giza 93 x Giza 86	12.74**	9.66**	49.71**	40.31**	52.40**	60.89**
Giza 93 x Giza 94	8.06**	3.20	51.90**	50.87**	46.98**	44.21**
Giza 96 x Giza 45	22.15**	19.04**	71.50**	64.79**	75.83**	71.02**
Giza 96 x Giza 86	5.31**	2.63	42.85**	33.63**	49.23**	38.41**
Giza 96 x Giza 94	5.69**	1.38	34.60**	34.89**	34.01**	35.79**
Giza 89 x Giza 45	-15.25**	-13.79**	27.13**	20.13	28.89**	21.74
Giza 89 x Giza 86	8.89**	2.19	42.02**	33.91**	44.26**	35.98**
Giza 89 x Giza 94	4.68**	4.59	19.97**	25.06**	16.20**	21.17**
Traits	Seed index SI		Lint percentage L%		Number of bolls/plant NB/P	
Genotypes	E1	E2	E1	E1	E2	E1
Giza 70 x Giza 45	11.91**	5.34**	3.97**	6.65*	41.57**	62.65**
Giza 70 x Giza 86	-6.39**	-6.06**	-1.70	3.94	26.46**	74.34**
Giza 70 x Giza 94	-1.08	5.08**	-0.54	4.40	-4.46	4.63
Giza 85 x Giza 45	14.00**	11.30**	4.88**	5.03*	3.30	14.56
Giza 85 x Giza 86	0.97	-0.43	2.74**	4.08	14.10**	11.77
Giza 85 x Giza 94	-1.08	-1.06	-2.03*	-1.56	17.88**	-0.64
Giza 87 x Giza 45	15.64**	16.71**	3.39**	5.16*	37.03**	47.31**
Giza 87 x Giza 86	0.11	3.04*	-1.98*	-0.89	-1.48	13.54
Giza 87 x Giza 94	5.97**	6.79**	1.03	2.09	39.69**	56.33**
Giza 92 x Giza 45	16.50**	12.11**	8.39**	7.85**	38.14**	40.63**
Giza 92 x Giza 86	3.20**	6.00**	-1.55	-2.70	8.00	23.03
Giza 92 x Giza 94	10.77**	12.03**	3.40**	4.38	32.31**	29.37**
Giza 93 x Giza 45	13.51**	11.44**	6.23**	5.10*	51.13**	58.24**
Giza 93 x Giza 86	2.96**	1.33	1.99*	1.57	33.30**	45.49**
Giza 93 x Giza 94	7.84**	6.11**	-1.33	-3.06	42.86**	49.26**
Giza 96 x Giza 45	13.40**	11.88**	5.35**	6.79**	43.52**	42.24**
Giza 96 x Giza 86	-2.56*	-3.29*	4.46**	3.76	35.56**	30.26**
Giza 96 x Giza 94	5.00**	8.17**	-0.10	0.78	27.76**	33.16**
Giza 89 x Giza 45	11.64**	10.73**	4.90**	4.74*	55.10**	44.47**
Giza 89 x Giza 86	5.08**	8.31**	1.82*	1.91	30.47**	31.08**
Giza 89 x Giza 94	-0.60	0.18	-2.97**	-3.05	14.78**	19.49*

Table 8. Heterosis (%) relative to better-parents (BP) for of the Egyptian cotton crosses under normal (E1) and drought (E2) stress conditions

Traits	Boll weight BW		Seed cotton yield/plant SCY		Lint yield/plant LY	
Genotypes	E1	E2	E1	E1	E2	E1
Giza 70 x Giza 45	-1.68	-3.24	31.45**	48.24**	33.89**	62.24**
Giza 70 x Giza 86	-17.06**	-20.55**	-6.57	20.34	-12.27**	18.92
Giza 70 x Giza 94	-8.36**	-10.67**	-30.35**	-24.65**	-36.84**	-30.37**
Giza 85 x Giza 45	9.69**	2.92	-8.66*	-7.88	-10.44*	-8.73
Giza 85 x Giza 86	5.22**	1.30	26.05**	15.29	29.24**	21.02
Giza 85 x Giza 94	1.45	1.86	11.36**	-0.37	4.17	-5.83
Giza 87 x Giza 45	-7.95**	-4.69	17.81**	33.47	18.95**	38.50
Giza 87 x Giza 86	9.80**	6.00	-2.39	12.78	-8.22	2.34
Giza 87 x Giza 94	-9.16**	-15.42**	1.99	5.81	-5.71	-0.63
Giza 92 x Giza 45	-0.80	-1.64	29.89**	30.32	38.63**	39.50
Giza 92 x Giza 86	3.02	-1.74	-0.97	13.91	-7.29	1.32
Giza 92 x Giza 94	0.43	-4.71	5.60	-0.61	-0.85	-4.78
Giza 93 x Giza 45	-5.34*	-7.83*	32.20**	34.76*	33.59**	34.67*
Giza 93 x Giza 86	8.06**	4.64	31.07**	23.64	31.56**	40.57**
Giza 93 x Giza 94	1.22	-3.09	17.01**	18.13*	8.30**	8.98
Giza 96 x Giza 45	10.65**	7.58*	31.76**	22.21*	27.28**	20.69
Giza 96 x Giza 86	4.68*	0.88	40.21**	24.95*	43.21**	27.06*
Giza 96 x Giza 94	2.57	-1.98	17.63**	25.00**	14.52**	23.47**
Giza 89 x Giza 45	-23.71**	-22.54**	-6.43	-14.11	-10.44**	-17.03
Giza 89 x Giza 86	8.78**	1.09	31.15**	18.78*	29.83**	18.14
Giza 89 x Giza 94	2.29	1.76	10.98**	22.51*	5.45	16.80
Traits	Seed index SI		Lint percentage L%		Number of bolls/plant NB/P	
Genotypes	E1	E2	E1	E1	E2	E1
Giza 70 x Giza 45	0.85	-2.99	1.88	3.40	33.63**	53.07**
Giza 70 x Giza 86	-10.15**	-9.70**	-6.15**	-4.74	12.63*	57.26**
Giza 70 x Giza 94	-8.05**	-1.58	-9.30**	-7.75**	-23.98**	-15.29
Giza 85 x Giza 45	-0.22	-1.82	-2.00*	-0.96	-16.89**	-10.49
Giza 85 x Giza 86	0.12	-1.24	2.49*	4.03	7.15	0.21
Giza 85 x Giza 94	-5.12**	-2.94	-6.42**	-5.39*	9.74*	-2.08
Giza 87 x Giza 45	4.20**	7.26**	0.93	3.64	27.72**	39.54*
Giza 87 x Giza 86	-3.89**	-0.73	-6.06**	-5.18*	-11.20*	1.79
Giza 87 x Giza 94	-1.48	0.23	-7.53**	-6.01*	12.28**	25.90**
Giza 92 x Giza 45	10.15**	8.14**	6.73**	6.93*	30.68**	32.05*
Giza 92 x Giza 86	-5.67**	-2.69	-6.45**	-7.46**	-4.02	11.22
Giza 92 x Giza 94	-1.77	0.35	-6.13**	-4.44	5.10	4.94
Giza 93 x Giza 45	1.02	0.36	1.05	0.14	39.64**	46.09**
Giza 93 x Giza 86	0.19	-0.21	0.32	0.52	21.16**	33.72**
Giza 93 x Giza 94	1.57	1.75	-7.43**	-7.80**	15.65**	22.80*
Giza 96 x Giza 45	-1.07	-0.87	-3.42**	-1.09	19.18**	13.65
Giza 96 x Giza 86	-3.02*	-3.57*	2.10*	1.75	32.37**	20.03
Giza 96 x Giza 94	1.08	5.58**	-2.66**	-1.33	14.63**	27.41**
Giza 89 x Giza 45	-3.13*	-3.07	-4.28**	-3.43	23.26**	11.11
Giza 89 x Giza 86	4.90**	6.51**	-0.98	-0.56	20.68**	15.26
Giza 89 x Giza 94	-3.72**	-0.86	-4.97**	-4.60	8.50*	18.61*

The highly significant difference of all genotypes (lines, testers, crosses, and parents vs. crosses) suggests that both additive and non-additive effects of genes governed the traits. The high degree of heterozygosity, or non-additive gene activities in the inheritance of these traits, is reflected in the substantial ($P \leq 0.01$) mean squares of parents vs. crosses, which leads to heterosis. However, because hybrid cotton is still not being used

commercially worldwide, the heterotic effects were not calculated. Also, the significant variability due to parents vs crosses for all the studied traits indicates the presence of hybrid vigor for these characters. These results are in line with those noted by Yehia et al. (2009) and El-Shazly et al. (2023) for Egyptian genotypes under stress conditions. The same results for the three Egyptian cotton varieties Giza 86, Giza 96, and Giza 94 for yield components traits were obtained by Yehia et al. (2021, 2024). In every way, none of the parents was better than the others. The parents were assigned the qualities with the best mean performance. All of the parents' attributes were significantly reduced as a result of the water scarcity stress.

A further analysis showed that general combining ability (GCA) and specific combining ability (SCA) variances for all the traits were all significant. In addition to a combining ability analysis three cotton varieties Giza 96, Giza 94 and Giza 98 could be considered as good combiners for all yield component traits and showed the best performance under normal and water scarcity stress. These two lines (Giza 96 and Giza 94) and tester (Giza 89) are depicted to be the good combiners for all yield traits, which may be due to their origin. The same results for the three Egyptian cotton varieties Giza 86, Giza 96, and Giza 94 for yield components traits were obtained by Abdel-Aty et al. (2023). In every way, none of the parents was better than the others. The parents were assigned the qualities with the best mean performance. All of the parents' attributes were significantly reduced as a result of the water scarcity stress. Also, the highly significant effects of specific combining ability (SCA) confirmed the preponderance of the non-additive effects in the inheritance of these traits as outlined by Yehia (2015) and El-Shazly et al. (2023). For the Egyptian cotton genotypes under Egyptian stress conditions. The variance due to SCA was greater than the variance due to GCA in terms of all traits studied in this research. It is clear that non-additive gene effects were dominant and control these characters genetically.

Genetic diversity is the main source of variability, which led to the development of new recombinants that were distinct from the parent and, ultimately, the discovery of heterosis. Additionally, the percentage difference in F_1 mean performance over both mid-parents and better-parents is used to represent heterosis. Heterosis suggests that F_1 crossings had higher adaptation because they were superior in certain qualities compared to their parents (Yehia and El-Hashash, 2021). According to the obtained results, the studied yield traits are generally thought to benefit from positive and significant heterosis over mid and better parents. Ten cotton crosses out of 21 F_1 had positive and highly significant over better-parent (BP) for the number of bolls/plants under normal and drought stress. Two and six cotton crosses showed negative and highly significant heterosis over better-parent (BP) for seed index and lint percentage, respectively. Similar results were reported by Al-Hibbiny et al. (2020) and Yehia et al. (2024) for the Egyptian cotton genotypes under Egyptian normal and drought stress conditions.

Selecting parents for hybridization breeding programs and choosing a suitable breeding technique for the genetic enhancement of the quantitative yield traits are made easier with an understanding of both gene action and genetic components. Therefore, the plant breeder needs to comprehend the type of gene action involved in the expression of diverse quantitative traits to create a successful cotton breeding program. The additive, dominance, and genetic variance components for the studied yield traits under normal and drought are displayed in Table 9. For every attribute, non-additive genetic variance was greater than additive genetic variance for all the studied yield traits under both normal and drought conditions, except for lint yield/plant under drought. Also, genetic variance showed higher values than environmental variance for boll weight, seed index, and number of bolls/plants under both conditions. While environmental variance was less than genetic variance for seed cotton yield, lint yield, lint

percentage, and number of bolls/plants under normal conditions only.

Both additive and dominant variances were equally important, indicating that both selection breeding and the use of heterosis can be effective. The results revealed that non-additive effects played a relatively large role in the manifestation of the studied traits, compared to additive effects. The results showed that the hybridization program would be effective in improving the majority of these yield traits. Likewise, some genetic studies on gene action in Egyptian cotton exhibited the importance of non-additive gene action for yield and its components (Al-Hibbiny et al., 2020; Yehia and El-Hashash, 2021, 2024; Yehia, 2022). In the self-pollinated crops, the non-additive gene action is predominant selection should be postponed to later generations. These results explain that the broad sense heritability (BSH) has the highest values than the narrow sense heritability (NSH) for all the studied yield traits under both normal and drought stress. The broad and narrow sense heritability showed higher values under normal than drought stress for the studied yield traits. Also, the high differences between broad and narrow sense heritability ratios may be due to the presence of non-fixable components in the inheritance of yield traits.

CONCLUSIONS

The significant parents-versus-crosses contrasts for all studied traits indicated the presence of significant average heterosis. Giza 89, Giza 94 and Giza 96 were identified as good general combiners for yield and its yield components under normal and drought stress. These varieties could be used to increase yield components in plant breeding programs. Giza 92 x Giza 45 exhibited significant and positive heterosis, however, Giza 70 x Giza 94 has negative and significant heterosis over better parents for all the studied traits. The non-additive gene effects were predominant for all the studied characters. High differences between broad and narrow sense heritability were observed.

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