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COMBINING ABILITY AND HETEROTIC STUDIES THROUGH LINE × TESTER IN LOCAL AND EXOTIC UPLAND COTTON GENOTYPES

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Abstract

Combining ability is mostly used by breeders to select appropriate parental cultivars to produce the larger progeny of new combinations through their hybridization. The objectives of this research were to estimate general combining ability of parents and specific combining abilities of F_1 hybrids, to identify suitable parents and hybrids for yield and its contributing traits, fiber quality parameters and also determine the heterosis in F_1 populations. In this study, 35 F_1 hybrids obtained by crossing five local lines (Turkey) with seven exotic testers (USA, Pakistan, Greece and Israel) in line × tester mating system during 2008 and were planted in randomized complete block design with four replications during 2009. Analysis revealed significant GCA and SCA mean squares for all the traits, however, non-additive gene action was predominant. Among parents, Sahin 2000 and Tamcot-22 were the best general combiners for yield and its components, and Carmen was the best general combiner for improvement in fiber quality. The best specific combinations were S-2000 × SJ-U86 and GSN-12 × NIAB-999 for boll number; BA-119 × DPL90 for boll weight; S-2000 × NIAB-999 for seed cotton yield; GSN-12 × Eva for fiber length; GSN-12 × AZ-31 and BA-119 × Tamcot-22 for fiber strength. In F_1 hybrids, the highest heterosis was observed for yield, boll number, boll weight and lint % with values of 79.8, 19.8, 35.2, and 5.7%, respectively. Heterosis values for fiber quality parameters were generally lower than that for yield components and 14.1% heterosis was observed for micronaire. The F_1 hybrids viz; Sahin-2000 × Tamcot-22, Sahin-2000 × NIAB-999, Carmen × Tamcot-22, and Carmen × NIAB-999 were noticed as high yielding hybrids with acceptable fiber quality parameters. Results also indicated that identification and selection of best new F_1 hybrids should not be only based on GCA and SCA, but it must be coupled with mean performance.

Introduction

Genetic diversity is the first step to create unique gene combinations for superior new cultivars. Thus, breeders tend to select genetically-diverse parents having different genes. In quantitative genetics, the genetic variance, which causes to produce transgressive segregation, increases as the parents carry different alleles. This theoretical concept is supported by some previous studies for soybean (Manjarrez-Sandoval *et al.,* 1997) and oat (Cowen and Frey, 1987) and observed that genetic variance was positively associated with parental genetic distance. In contrast, Helms *et al.,* (1997) and Kisha *et al.,* (1997) reported that genetic distance for soybean lines was not related with genetic variance. Furthermore, Martin *et al.,* (1995) working with wheat (*Triticum aestivum* L.) found no association between measures of diversity and hybrid performance. Meredith and Brown (1998) using restriction fragment length polymorphic (RFLP) markers reported that in cotton the correlations between yield of F_2 hybrids, heterosis, and genetic distance were very low. It was assumed that a large genetic distance among parents facilitates the development of superior progeny. Unlike this, Meredith (1998) and Campbell *et al*., (2008) reported that in cotton increased genetic distance was not a good predictor of heterosis. Van Esbrocek & Bowman (1998) observed that parental genetic diversity, as estimated by coefficient of parentage, was not imperative for cotton improvement.

Successful cultivars were most frequently developed from high-yielding, closely-related and locally-adapted cultivars. Van Esbrocek & Bowman (1998) proposed two probable explanations for the weak relationship between parental genetic diversity and cultivar improvement. First possible explanation was that there may be sufficient allelic variation, mutation, or recombination in the mating of closely-related individuals to result in improved agronomic performance. The second possible explanation for the weak relationship between diverse parental coefficient of parentage and cultivar success is that coefficient of parentage may not reflect the true genetic distance. They also reported that recombination rates in distantly-related genotypes might be reduced because of improper pairing during meiosis due to extensive differences in DNA sequences. In a study involving 64 F_2 hybrids obtained from 20 parents, highest lint yields and heterosis were obtained from the cross of the closely-related lines (Tang *et al.,* 1993). Furthermore, Souza & Sorrells (1991) reported an initial increase in genetic variance or hybrid vigor with increasing genetic distance followed by decline at high genetic distance. In cotton, high recombination between adapted and un-adapted parental genotypes can break up favorable linkage groups such that progenies no longer contain the favorable allele combinations (Van Esbrocek & Bowman, 1998).

Exploitation of heterosis is used to increase cotton yields in countries where a cheap labor force is available to make hand emasculation and crossing (Chaudhry, 1997). The major limiting factor in using heterosis for hybrid cotton production is the lack of an efficient and dependable system for producing F_1/F_2 hybrids seed mainly due to the ineffectiveness of the male gametocide (Meredith & Brown, 1998), and the inconsistency of results from male sterile and restorer factors (Percy & Turcotte, 1991). In cotton producing countries, China and India have rapidly adopted hybrid cotton production systems and increased the yield. According to Dongre & Parkhi (2005), hybrid cotton in India represents approximately 45% of the total production area and accounts for about 55% of India's cotton production. Dong *et al*., (2006) reported that hybrid cotton production in China since 2000 covers approximately 20% of the total acreage. Previous studies have also demonstrated a close relationship between parental performance and their hybrids (Miller & Lee, 1964; Davis, 1978; Wu *et al.,* 2004). However, Meredith & Brown (1998) reported that unexplained variability due to primarily non-additive genetic effects would hinder the selection of hybrid parents based on parental performance alone and suggested that parents should be assorted on their known combining ability. In previous review, it was reported that seed cotton yield heterosis ranged from 15.5% (Al-Rawi & Kohel, 1969) to 35% (Thomson and Luckett, 1988). Also, the findings using more data (Meredith, 1998) showed an average useful heterosis of 21.4% for F_1 hybrids. Campbell *et al.,* (2008) reported that the obsolete group of cultivars showed average lint yield heterosis values of 34% compared with 23% for the modern cultivars.

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The heterosis of F_1 hybrids can also reflect general combining ability (GCA) and specific combining ability (SCA) of parental lines. Combining ability and heterotic studies have been conducted to screen cotton germplasm to determine their ability to be included or not in a breeding programme on the basis of their GCA, SCA and heterotic effects (Khan *et al.,* 2009). Combining ability describes the potential ability of parental lines to produce hybrids. To develop new cotton cultivars, the first step is to select appropriate parents and hybridize selected parents to produce large populations of progeny and then these populations can be evaluated based on traits of interest to select individuals and/or families. In order to choose appropriate parents and crosses, and to estimate the combining abilities of parents in the early generation, the line × tester analysis method has been widely used by plant breeders in self and cross pollinated crops (Konak *et al.,* 1999; Mert *et al.,* 2003; Basbag *et al.,* 2007, Ahuja & Dhayal 2007; Basal *et al.,* 2009). Sprague & Tatum (1942) used the term GCA to designate the average performance of a genotype in hybrid combinations and used the terms SCA to define those cases in which certain combinations do relatively better or worse than expected on the basis of the average performance of the genotypes involved.

Previous studies showed that yield and yield contributing traits were influenced by non-additive (Shakeel *et al.,* 2001; Ahuja and Dhayal 2007), additive and non-additive (Kumaresan *et al.,* 1999; Basal & Turgut 2005) gene effects. Hassan *et al*., (2000) and Ahuja & Dhayal (2007) reported the non-additive gene action for fiber quality parameters. Cheatham *et al*., (2003) indicated that lint % and fiber strength exhibited primarily additive, micronaire and fiber length exhibited primarily dominance genetic effects. A number of researchers reported significant GCA for basic yield components and fiber quality parameters (Green & Culp 1990; Coyle & Smith 1997; Basal & Turgut 2003; Ahuja & Dhayal 2007; Basal *et al.,* 2009).

The purposes of this study were (i) to estimate general and specific combining abilities for yield, its components and fiber quality parameters among five local genotypes (developed at Turkey) were taken as female parents and seven exotic testers (originated at four different cotton growing countries) of *G. hirsutum*; (ii) to identify appropriate parents and crosses for the investigated traits; and (iii) to determine heterosis for 35 F_1 populations developed by line × tester mating system.

Material and Methods

Breeding material and field procedure: The genetic population was developed through line × tester (5 × 7) mating design. The five well adapted current Turkish commercial cotton cultivars (Carmen, STN-453, S-2000, GSN-12, BA-119) were used as lines and were hand crossed with seven exotic cotton cultivars treated as testers originated from four different countries (Tamcot-22, SJ-U86, and DPL-90 from USA; NIAB-999 and NIAB-111 from Pakistan; Eva from Greece; AZ-31 from Israel) during 2008 at Agriculture Faculty, Adnan Menderes University, Turkey. Parents and their 35 F_1 populations were grown in one row plots having 6 m length in a randomized complete block (RCB) design with three replications during 2009. The rows and plants spacing were 0.70 and 0.20 m, respectively. Cultural practices were common for cotton production in western Turkey.

Traits measurement and statistical analysis: Twenty well developed open bolls were randomly hand harvested from each row of parents and F_1's. The bulked bolls from each genotype were ginned. The seed cotton weight per boll (SCW/B) and lint % (LP) were obtained from each boll sample. A high volume instrument (HVI) was used to measure fiber length (UHM), fiber strength (Str.), fiber uniformity (UI), micronaire (Mic.) and fiber elongation (%). All the recorded data were subjected to analysis of variance (ANOVA) technique for a RCB design as outlined by Steel & Torrie (1980) through Mstatc computer programme for all the traits to test the null hypothesis of no differences among the cotton genotypes. The genotypes means for each parameter were further separated and compared by using the least significant difference (LSD) test at 5% level of probability. The GCA and SCA variance effects of parents and F_1 hybrids, respectively were estimated by using line × tester analysis method as described by Kempthorne (1957). The heterosis values were also tested for significance to establish the difference of F_1 hybrids means from their respective mid parents by applying t test with the following formula as quoted by Wynne *et al.,* (1970).

$$t = \frac{F_{1ij} - MP_{ij}}{\sqrt{(\frac{3}{8})\ EMS}}$$

where

F_1ij = Mean of the ijth F_1 cross.
MPij = Mid parent value for the ijth cross.
EMS = Error mean square.

Results

Significant differences were detected among parents and F_1 hybrids for yield and yield components, and fiber quality traits indicating the presence of genetic diversity among them (Table 1). The data showed that the parents or crosses didn't follow the same pattern for investigated traits. The ratio of σ^2GCA/σ^2SCA was smaller than zero for all the characters indicating predominance of non-additive gene action (dominant or epistasis) in the inheritance of investigated traits. Several studies have been conducted to estimate the gene action for yield and yield contributing traits, and fiber quality parameters. However, they reported inconsistent results including non-additive (Shakeel *et al.,* 2001; Ahuja & Dhayal, 2007; Khan *et al.,* 2009), additive as well as non-additive (Kumaresan *et al.,* 1999; Basal & Turgut, 2005; Basal *et al.,* 2009), and additive gene action (Chinchane *et al.,* 2002; Khan *et al.,* 2005; Aguiar *et al.,* 2007; Lukonge *et al.,* 2007) for the yield components and fiber quality traits. Contradictions may be due to different genetic backgrounds of cultivars used and environmental conditions under which the studies were conducted.

The proportional contributions of lines and testers and their interactions (line × tester) to the total variance were varied among the investigated characters (Table 2). Results revealed that line × tester interactions made greater contribution to the total variance for most of the traits i.e., yield, boll number, boll weight, uniformity index and micronaire. Proportional contribution of lines to total variance was highest for fiber length, fiber strength and fiber elongation. Testers had the maximum contribution only for lint percentage. It is evident that the maximum contributions to the total variance for most of the characters were made by line × tester interactions and lines (Table 2).

The parents varied significantly for each character (Table 3). Bolls per plant varied from 7.8 (Tamcot-22) to 14.6 (NIAB-999) among the parents. BA-119 had the lowest boll weight (5.1 g) but the highest lint percentage (41.4%). Eva and AZ-31 produced bolls over 7.0 g. Seed cotton yield was between 3153 (DPL90) and 5405 (AZ-31) kg ha^{-1}. NIAB-111 exhibited the longest fibers (31.6 mm UHM length), while STN-453 had the shortest UHM length of 27.8 mm. Among parents, AZ-31, Carmen, and NIAB-999 had the strongest fibers, ranging from 34.1 to 35.9 g/tex, and STN-453 had the weakest fibers (27.4 g/tex). Length uniformity (UI) was varied from 86.5 (NIAB-111) to 83.3 % (STN-453). NIAB-111 had the lowest micronaire value (3.8 units) and STN-453 had the highest value of 5.1 units. In case of fiber elongation, the lowest (4.7%) and highest (6.8%) values were produced by AZ-31 and NIAB-111, respectively.

Significant GCA effects were detected for yield components, seed cotton yield and fiber quality traits (Table 4). Among the parents, STN-453, Sahin-2000, SJ-U86, and NIAB-999 exhibited high GCA effects for bolls per plant. Line Sahin-2000 and tester Tamcot-22 were identified as good source of favorable genes in improving seed cotton yield. Unlike Carmen, which contributed low GCA for lint percentage, the cultivars BA-119 and Tamcot-22 were determined to be the good general combiners for lint percentage. Carmen would be the genotype to be used to develop progeny having good fiber quality except fiber elongation. Other best general combiners for fiber quality parameters were STN-453 for fiber length, Sahin-2000, BA-119, and NIAB-111 for fiber elongation, Tamcot-22 for fiber length and elongation, SJ-U86 for fiber length and strength and AZ-31 for fiber strength.

The SCA effects revealed that the best specific combinations were the F_1 hybrids i.e. S-2000 × SJ-U86, GSN-12 × NIAB-999 and BA-119 × DPL90 for boll number; BA-119 × DPL90 for boll weight; S-2000 × NIAB-999, BA-119 × AZ-31 and BA-119 × DPL90 for seed cotton yield; GSN-12 × Eva for fiber length; GSN-12 × AZ-31 and BA-119 × Tamcot-22 for fiber strength (Table 5). Some of these crosses were related with GCA effects of their parents having at least one parent with high or average GCA effects for the particular trait. Results authenticated that high × low and low × high general combiners were responsible for presentation of desirable SCA along with remarkable mean performance. However, some of the best specific combinations viz; BA-119 × DPL90 for boll number and seed cotton yield; GSN-12 × Eva for fiber length and BA-119 × Tamcot-22 for fiber strength, were obtained from parents having low and even negative GCA effects, means that some desirable SCA effects of F_1 hybrids were administered by low GCA parents.

Table 1. Means squares for yield, its components and fiber quality parameters.

Source of variation	D.F.	BN/P	BW	LP	Yield	UHM	Str.	UI	Mic.	Elongation
Replications	2	37.2**	0.58	0.54	328085**	3.65*	0.95	2.44	0.160	0.450*
Genotypes	46	10.5**	1.43**	5.40**	23673**	5.03**	10.22**	2.64**	0.248**	0.680**
Parents	11	13.7**	1.73**	10.16**	19818**	5.24**	16.58**	2.85*	0.357**	1.061**
Parents vs. hybrids	1	0.51	2.90**	1.44	10179	2.58	0.02	0.87	0.158	0.124
Hybrids	34	9.7**	1.29**	3.98**	25308**	5.04**	8.47**	2.63**	0.215**	0.573**
Females	4	13.9	1.74	8.78**	62916*	20.18**	30.98**	8.26*	0.405*	2.188**
Males	6	21.2*	2.11	10.70**	35331	5.76	16.57**	1.55	0.439**	1.439**
Females × males	24	6.2**	1.00	1.51	16548**	2.33**	2.69**	1.96	0.128	0.087
Error	92	2.97	0.618	1.736	6384.8	1.037	1.333	1.385	0.093	0.117
σ^2 GCA		0.070	0.006	0.048	171.3	0.053	0.113	0.013	0.002	0.009
σ^2 SCA		1.073	0.129	-0.077	3387.8	0.432	0.452	0.191	0.012	-0.010
σ^2 GCA / σ^2 SCA		0.065	0.046	-0.623	0.051	0.123	0.250	0.068	0.166	-0.900

*, ** Significant at p≤0.05 and p≤0.01, respectively; BN/P: Bolls per plant; BW: Boll weight; LP: Lint %; Yield: Seed cotton yield; UHM: Upper half mean fiber length; Str: Fiber bundle strength; UI: Uniformity index; Mic: Micronaire; σ^2GCA: GCA variance; σ^2SCA: SCA variance

Table 2. Proportional contributions of lines, testers and their interaction to total variance for various traits.

Source of variation	D.F.	BN/P (No)	BW (g)	LP (%)	Yield (kg ha^{-1})	UHM (mm)	Str. (g/tex)	UI (%)	Mic. (units)	Elongation (%)
Lines (females)	4	16.77	15.89	25.92	29.23	47.14	43.04	36.98	22.14	44.94
Testers (males)	6	38.41	28.98	47.38	24.62	20.17	34.52	10.44	36.02	44.32
Lines × Testers	24	44.82	55.12	26.69	46.14	32.69	22.43	52.56	41.83	10.72
Error	92	2.97	0.618	1.736	6384.8	1.037	1.333	1.385	0.093	0.117

Table 3. Mean performance of parental cultivars for yield, its components and fiber quality parameters.

Parents	BN/P (No)	BW (g)	LP (%)	Yield (kg ha^{-1})	UHM (mm)	Str. (g/tex)	UI (%)	Mic. (units)	Elongation (%)
Carmen	9.9 cde	6.6 ab	40.7 ab	3520 c	28.8 cde	34.2 ab	85.6 a-d	4.7 ab	5.1 ef
STN-453	8.7 de	5.5 bc	41.2 a	3167 c	27.8 e	27.4 f	83.3 d	5.1 a	5.8 cde
Sahin-2000	11.5 bcd	5.6 bc	37.5 cde	3774 c	29.3 b-e	28.6 ef	84.2 bcd	4.5 bc	6.5 ab
GSN-12	9.7 cde	6.9 ab	38.5 bcd	3875 bc	28.4 de	31.3 d	84.5 a-d	4.8 ab	5.4 e
BA-119	10.3 cde	5.1 d	41.4 a	3676 c	28.2 de	30.5 de	83.9 ed	4.6 abc	6.1 bcd
Tamcot-22	7.8 e	6.6 ab	40.7 ab	3412 c	28.7 cde	31.8 cd	84.5 a-d	4.3 bcd	6.4 abc
SJ-U86	12.7 abc	6.9 ab	38.4 bcd	4936 a	31.4 ab	33.8 abc	86.4 ab	4.4 bcd	5.7 de
NIAB-999	14.6 a	6.7 ab	39.0 a-d	5209 a	30.1 a-d	34.1 ab	85.6 a-d	4.6 abc	5.5 de
NIAB-111	13.6 ab	5.8 bc	37.7 cde	4779 ab	31.6 a	31.6 cd	86.5 a	3.8 e	6.8 a
Eva	8.5 de	7.3 a	35.7 e	3545 c	30.3 a-d	30.6 de	85.8 abc	4.1 de	5.6 de
AZ-31	9.9 cde	7.4 a	36.7 de	5405 a	30.9 abc	35.9 a	85.8 abc	4.6 abc	4.7 f
DPL-90	9.9 cde	6.8 ab	39.7 abc	3153 c	29.7 a-e	32.7 bcd	84.7 a-d	4.8 ab	5.8 cde
$LSD_{(0.05)}$	3.05	1.48	2.49	950.4	2.16	2.28	2.35	0.61	0.68

Values followed by same letter within column didn't differ at p≤0.05

Table 4. General combining ability effects of parental cultivars for yield, its components and fiber quality parameters.

Parents	BN/P[1] (No)	BW (g)	LP (%)	Yield (kg ha^{-1})	UHM (mm)	Str. (g/tex)	UI (%)	Mic. (units)	Elongation (%)
					Lines				
Carmen	-0.261	0.189	-0.668*	16.21	1.264**	1.973**	0.937**	-0.141*	-0.372**
STN-453	0.887*	0.275	-0.596*	3.90	0.640**	0.273	0.347	0.007	0.013
Sahin-2000	0.8150*	0.154	-0.010	68.37**	-0.093	-1.089	-0.296	-0.108	0.399**
GSN-12	-0.504	-0.258	0.446	-4.76	-0.601**	-0.384	-0.482	0.031	-0.263**
BA-119	-0.9370*	-0.360*	0.809**	-83.72**	-1.211**	-0.774**	-0.506	0.211**	0.223**
					Testers				
Tamcot-22	0.261	0.314	1.626**	66.59**	0.581*	-0.213	0.095	-0.080	0.198*
SJ-U86	1.241**	0.255	0.359	-7.29	0.554*	0.913**	0.102	0.077	-0.215*
NIAB-999	1.634**	-0.421*	-0.008	30.11	0.435	0.340	-0.011	-0.146	-0.082
NIAB-111	0.094	-0.595**	-0.394	-1.49	0.136	-1.127**	0.069	-0.220	0.511**
Eva	-1.739**	0.073	-0.814*	-59.43**	-0.934**	-1.340**	-0.391	-0.040	0.011
AZ-31	-0.939*	0.382	-0.828*	34.74	-0.011	1.593**	0.535	0.269**	-0.469**
DPL90	-0.552	-0.008	0.059	-63.23**	-0.760**	-0.167	-0.398	0.140	0.045
S.E.(Lines)	0.377	0.172	0.288	17.44	0.222	0.252	0.257	0.067	0.075
S.E.(Testers)	0.446	0.203	0.340	20.63	0.263	0.298	0.304	0.079	0,088

*, ** Significant at *p≤0.05* and *p≤0.01*, respectively

Table 5. Specific combining ability effects of F_1 hybrids for yield, its components and fiber quality parameters.

F_1 hybrids	BN/P (No)	BW (g)	LP (%)	Yield (kg ha^{-1})	UHM (mm)	Str. (g/tex)	UI (%)	Mic. (units)	Elongation (%)
Carmen × Tamcot-22	1.33	0.06	-0.55	48.8	-0.34	-1.23	0.51	-0.01	0.15
Carmen × SJ-U86	-1.25	-0.42	0.17	-44.4	-0.20	-0.24	0.01	0.09	0.03
Carmen × NIAB-999	-1.34	0.22	1.07	-32.4	-0.85	0.29	-0.18	0.32	-0.09
Carmen × NIAB-111	0.10	-0.12	-0.27	26.1	1.05	0.19	0.20	-0.24	-0.02
Carmen × Eva	0.63	-0.02	-0.31	2.7	0.38	0.60	0.03	-0.21	0.04
Carmen × AZ-31	0.60	0.36	-1.03	1.4	0.46	0.01	-0.66	-0.05	0.12
Carmen × DPL90	-0.08	-0.08	0.94	-2.1	-0.49	0.40	0.10	0.10	-0.25
STN-453 × Tamcot-22	-1.38	-0.12	0.03	-40.3	-0.58	-1.15	-0.70	0.05	0.07
STN-453 × SJ-U86	0.11	-0.04	0.87	40.3	-1.08	0.72	-1.04	-0.06	0.02
STN-453 × NIAB-999	-0.18	-0.09	0.53	12.9	0.13	0.56	-0.09	0.16	-0.04
STN-453 × NIAB-111	0.85	-0.20	-0.54	-28.8	0.90	1.06	1.46	-0.14	-0.24
STN-453 × Eva	1.15	0.39	0.37	9.7	0.07	-0.72	0.52	0.06	0.22
STN-453 × AZ-31	-0.05	-0.11	-0.14	27.2	0.15	-0.46	-0.14	-0.12	-0.02
STN-453 × DPL90	-0.50	0.18	-1.13	-21.1	0.40	0.00	-0.01	0.04	-0.01
Sahin-2000 × Tamcot-22	0.36	0.24	0.48	88.1	0.17	0.20	0.34	0.05	0.05
Sahin-2000 × SJ-U86	2.38*	-0.03	0.15	-8.7	0.31	-0.01	0.33	0.23	0.06
Sahin-2000 × NIAB-999	-0.02	0.29	-0.68	94.6*	0.48	-0.14	0.25	0.05	-0.06
Sahin-2000 × NIAB-111	1.26	0.01	0.27	65.4	0.28	-0.67	-0.06	-0.14	0.20
Sahin-2000 × Eva	-1.54	0.59	-0.71	-71.6	-0.33	-0.13	-0.43	-0.01	-0.39*
Sahin-2000 × AZ-31	-2.21*	-0.47	0.87	-168.4**	-1.39*	-0.19	0.86	0.18	-0.01
Sahin-2000 × DPL90	-0.23	-0.63	-0.38	0.6	0.47	0.96	0.43	-0.37*	0.14
GSN-12 × Tamcot-22	-0.86	-0.19	0.44	-42.5	0.03	0.93	-0.40	-0.10	-0.35
GSN-12 × SJ-U86	-1.04	0.50	-0.42	55.1	0.57	-0.42	0.88	-0.07	-0.01
GSN-12 × NIAB-999	2.77**	-0.30	-0.65	53.5	0.42	-0.85	-0.89	-0.38*	0.16
GSN-12 × NIAB-111	-0.49	0.42	0.16	-15.3	-0.91	0.35	-0.57	0.17	0.07
GSN-12 × Eva	0.28	0.29	-0.05	6.2	1.20*	0.83	0.94	0.13	0.10
GSN-12 × AZ-31	0.94	0.37	-0.27	26.8	0.13	1.39*	1.18	0.08	0.05
GSN-12 × DPL90	-1.61	-1.09*	0.80	-83.9	-1.46*	-2.43**	-1.14	0.16	-0.03
BA-119 × Tamcot-22	0.54	0.01	-0.40	-54.1	0.76	1.26*	0.52	-0.01	0.06
BA-119 × SJ-U86	-0.20	-0.01	-0.76	-42.4	0.39	-0.03	-0.18	-0.19	-0.12
BA-119 × NIAB-999	-1.23	-0.11	-0.26	-128.6**	-0.18	0.14	0.92	-0.16	0.04
BA-119 × NIAB-111	-1.72	-0.10	0.38	-47.1	-1.33*	-0.92	-1.02	0.36*	-0.01
BA-119 × Eva	-0.52	-1.25**	0.70	52.9	-1.32*	-0.57	-1.06	0.02	0.01
BA-119 × AZ-31	0.71	-0.15	0.58	112.9*	0.63	-0.74	0.47	-0.09	-0.13
BA-119 × DPL90	2.42*	1.62**	-0.23	106.5*	1.08	0.88	0.61	0.06	0.15
S.E.	0.99	0.45	0.76	46.1	0.58	0.66	0.68	0.17	0.19

*, ** Significant at *p≤0.05* and *p≤0.01*, respectively.

Mean performance and heterotic values of 35 F_1 hybrids for yield related traits and fiber quality revealed that majority of the F_1 hybrids produced higher values as compared to parental cultivars (Table 6a & b). Bolls per plant ranged from 14.6 (GSN-12 × NIAB-999) to 7.5 (BA-119 × Eva) among the F_1 hybrids. The highest positive and significant heterosis for boll number (35.2%) was detected in Carmen × Tamcot-22. The boll weight varied from 8.1 (BA-119 × DPL90) to 5.3 g (BA-119 × Eva) among the F_1 hybrids, while the estimated highest heterosis for boll weight was 35.2% (BA-119 × DPL90). The highest and lowest lint percentages were recorded in GSN-12 × Tamcot-22 (41.7 %) and Carmen × AZ-31 (36.6 %), respectively. The heterotic values for lint percentage ranged between 0.5 to 5.7%, and 18 hybrids showed positive heterosis. In 35 F_1 hybrids, the seed cotton yield varied from 2409 to 6462 kg ha^{-1} among the F_1 crosses. Maximum yield (6462 kg ha^{-1}) was obtained from Sahin-2000 × Tamcot-22 followed by Sahin-2000 × NIAB-999 (6163 kg ha^{-1}), Sahin-2000 × NIAB-111 (5555 kg ha^{-1}), Carmen × Tamcot-22 (5549 kg ha^{-1}), Carmen × NIAB-999 (5224 kg ha^{-1}), and GSN-12 × NIAB-999 (5021 kg ha^{-1}). Among crosses, 23 F_1 hybrids showed positive heterosis for yield varying between 3.5 and 79.8%. The hybrids Sahin-2000 × Tamcot-22, Sahin-2000 × NIAB-999, Sahin-2000 × NIAB-111 and Carmen × Tamcot-22 were having highest yield along with significant positive heterosis for seed cotton yield. Fiber length ranged from 32.4 (Carmen × NIAB-111) to 26.5 mm (GSN-12 × DPL90) among the F_1 progenies. The strongest fibers (36.3 g/tex) were produced by F_1 hybrid Carmen × AZ-31. Fiber uniformity index values of 35 F_1 hybrids were between 87.2 and 83.3%. The estimated maximum heterosis values for fiber length, fiber bundle strength, and uniformity index were 9.6, 9.9, and 2.7%, respectively.

Table 6a. Mean performance and heterosis of F_1 hybrids for yield, its components and fiber quality parameters.

F_1 hybrids	BN/P[1] (No)	BW (g)	LP (%)	Yield (kg ha^{-1})	UHM (mm)	Str. (g/tex)	UI (%)	Mic. (units)	Elongation (%)
Carmen × Tamcot-22	12.0	7.4	39.6	5549	31.5	32.3	86.9	4.27	5.73
	(35.2)[2] **	(10.1)	(-2.7)	(60.1)**	(9.6)**	(-2.1)	(2.1)*	(-6.2)	(-0.6)
Carmen × SJ-U86	10.4	6.8	39.0	3877	31.6	34.4	86.4	4.52	5.20
	(-7.9)	(0.6)	(-1.3)	(-8.3)	(5.1)*	(1.9)	(0.4)	(-1.8)	(-3.7)
Carmen × NIAB-999	11.7	6.8	39.6	5224	30.8	34.4	86.1	4.52	5.20
	(-5)	(2.3)	(-0.7)	(19.7)	(4.8)*	(0.6)	(0.5)	(-3.4)	(-2.5)
Carmen × NIAB-111	10.6	6.3	37.8	4640	32.4	32.8	86.5	3.88	5.87
	(-10)	(1.1)	(-3.5)	(11.8)	(7.4)**	(-0.2)	(0.5)	(-9.8)*	(-1.7)
Carmen × Eva	9.3	7.0	37.4	3826	30.7	33.0	85.9	4.10	5.43
	(1.1)	(1.1)	(-2.1)	(8.3)	(4.0)	(1.9)	(0.2)	(-7.4)	(0.9)
Carmen × AZ-31	10.1	7.7	36.6	4756	31.7	36.3	86.1	4.57	5.03
	(1.3)	(10.1)	(-5.3)*	(6.6)	(6.3)**	(3.7)	(0.5)	(-2.4)	(2.4)
Carmen × DPL90	9.8	6.9	39.5	3741	29.9	33.9	85.9	4.59	5.17
	(-1.8)	(2.7)	(-1.7)	(12.1)	(2.6)	(1.6)	(0.9)	(-4.3)	(-5.5)
STN-453 × Tamcot-22	11.0	7.2	40.2	4534	30.6	30.7	85.1	4.47	6.03
	(33.2) *	(18.1)*	(-1.7)	(37.8)	(8.4)**	(3.7)	(1.4)	(-5.9)	(-1.1)
STN-453 × SJ-U86	12.2	7.3	39.8	4602	30.1	33.7	84.7	4.51	5.57
	(13.7)	(16.7)*	(-0.1)	(13.6)	(1.8)	(9.9)**	(-0.1)	(-6.1)	(-2.9)
STN-453 × NIAB-999	13.0	6.6	39.1	4702	31.2	32.9	85.6	4.51	5.63
	(11.5)	(7.4)	(-2.5)	(12.3)	(7.9)**	(7)**	(1.3)	(-7.8)*	(-0.6)
STN-453 × NIAB-111	11.7	6.3	37.6	3967	31.6	32.0	87.2	4.13	6.03
	(4.8)	10.7)	(-4.7)*	(-0.12)	(6.6)**	(8.4)**	(2.7)**	(-8.5)*	(-4.2)
STN-453 × Eva	10.6	7.5	38.1	3768	29.7	30.0	85.8	4.52	6.00
	(23.3)	(17.3)*	(-0.9)	(12.3)	(2.6)	(3.3)	(1.5)	(-2.3)	(4.9)
STN-453 × AZ-31	11.6	7.3	37.6	4890	30.7	32.6	86.1	4.64	5.27
	(24.5)*	(13.1)	(-3.5)	(14.1)	(4.9)*	(5.1)*	(1.8)*	(-5.1)	(0.3)
STN-453 × DPL90	10.5	7.3	37.5	3427	30.3	31.8	85.3	4.68	5.80
	(12.2)	(17.4)*	(-7.3)**	(8.5)	(5.3)*	(6.1)*	(1.5)	(-6.4)	(0.0)
Sahin-2000 × Tamcot-22	12.1	7.5	41.3	6462	30.6	30.7	85.5	4.36	6.40
	(25.4)*	(21.6)**	(5.6)**	(79.8)**	(5.5)*	(1.5)	(1.3)	(-1.7)	(-0.8)
Sahin-2000 × SJ-U86	11.0	7.2	39.7	4757	30.8	31.6	85.5	4.69	6.00
	(-9)	(14.3)	(4.5)*	(9.2)	(1.3)	(1.1)	(0.2)	(4.7)	(-1.3)
Sahin-2000 × NIAB-999	13.1	6.8	38.5	6163	30.8	30.9	85.3	4.29	6.00
	(0.4)	(11.3)	(0.6)	(37.2)**	(3.7)	(-1.6)	(0.4)	(-6.0)	(-0.3)
Sahin-2000 × NIAB-111	12.8	6.4	39.0	5555	30.3	28.9	85.0	4.02	6.87
	(2.3)	(11.5)	(3.7)	(29.9)*	(-0.6)	(-4.1)	(-0.4)	(-3.9)	(3.7)
$LSD_{(0.05)}$	2.32	1.24	2.03	829.4	1.87	1.95	1.91	0.46	0.51
S.E.(Heterosis)	1.056	0.481	0.807	48.93	0.623	0.707	0.721	0.186	0.209

Upper and lover values denote mean performance and heterosis, respectively

Table 6b. Mean performance and heterosis of F_1 hybrids for yield, its components and fiber quality parameters.

Crosses	BN/P[1] (No)	BW (g)	LP (%)	Yield ($kg\ ha^{-1}$)	UHM (mm)	Str. (g/tex)	UI (%)	Mic. (units)	Elongation (%)
Sahin-2000 × Eva	8.2	7.6	37.6	3605	28.6	29.2	84.2	4.33	5.77
	(-17.6)	(17.9)*	(2.8)	(-1.5)	(-3.9)	(-1.4)	(-0.9)	(0.5)	(-4.9)
Sahin-2000 × AZ-31	8.3	6.9	39.2	3579	28.5	32.1	84.7	4.84	5.67
	(-22.5)*	(5.2)	(5.7)**	(-22.1)	(-5.4)*	(-0.7)	(-0.3)	(6.03	(1.2)
Sahin-2000 × DPL-90	10.7	6.3	38.8	4290	29.6	31.5	85.1	4.14	6.33
	(-0.3)	(1.6)	(0.5)	(23.9)	(0.2)	(2.6)	(0.7)	(-11.5)**	(2.9)
GSN-12 × Tamcot-22	9.6	6.7	41.7	4425	30.0	32.1	84.5	4.34	5.33
	(9.3)	(-2.7)	(5.3)*	(21.5)	(5)*	(1.8)	(0.1)	(-5.9)	(-9.6)**
GSN-12 × SJ-U86	10.4	7.3	39.57	4663	30.5	31.9	85.8	4.52	5.27
	(-7.3)	(4.9)	(2.8)	(5.8)	(2.1)	(-2.1)	(0.4)	(-2.9)	(-4.8)
GSN-12 × NIAB-999	14.6	5.8	39.00	5021	29.6	30.9	83.9	3.99	5.57
	(19.8)*	(-14.5)*	(0.6)	(10.5)	(1.2)	(-5.6)*	(-1.3)	(-15.9)**	(1.8)
GSN-12 × NIAB-111	9.8	6.4	39.4	4016	28.9	30.6	84.3	4.48	6.07
	(-16.2)	(-0.1)	(3.3)	(-7.2)	(-3.6)	(-2.6)	(-1.4)	(2.5)	(-0.5)
GSN-12 × Eva	8.7	6.9	38.8	3652	28.6	30.9	85.4	4.62	5.60
	(-4.5)	(-3.1)	(4.5)*	(-1.5)	(-2.3)	(-0.3)	(0.2)	(2.9)	(1.5)
GSN-12 × AZ-31	10.2	7.3	38.5	4800	29.5	34.4	86.6	4.87	5.07
	(3.2)	(1.5)	(2.4)	(3.5)	(-0.4)	(2.2)	(1.6)	(2.7)	(0.3)
GSN-12 × DPL-90	8.0	5.4	40.5	2713	26.5	29.0	83.3	4.82	5.50
	(-18.7)	(-20.9)**	(3.5)	(-22.8)	(-8.8)**	(-9.4)**	(-1.6)	(-0.8)	(-1.8)
BA-119 × Tamcot-22	10.5	6.7	41.2	3520	30.1	32.0	85.2	4.61	6.23
	(16.6)	(14.0)	(0.5)	(-0.7)	(5.7)*	(2.9)	(1.1)	(2.7)	(-0.3)
BA-119 × SJ-U86	10.7	6.7	39.6	2898	29.7	31.9	84.7	4.59	5.63
	(-6.5)	(10.7)	(-0.8)	(-32.7)**	(-0.1)	(-0.9)	(-0.53	(1)	(-4.2)
BA-119 × NIAB-999	10.1	5.9	39.7	2409	29.0	31.5	85.7	4.39	5.93
	(-18.5)*	(0.1)	(-1.2)	(-45.7)**	(-0.3)	(-2.6)	(1.1)	(-5.1)	(2)
BA-119 × NIAB-111	8.1	5.7	40.0	2906	27.6	27.9	83.9	4.84	6.47
	(-32.4)**	(5.1)	(1.1)	(-31.2)**	(-7.8)**	(-9.9)**	(-1.6)	(14.1)**	(0.3)
BA-119 × Eva	7.5	5.3	39.8	3330	26.5	29.1	83.4	4.68	6.00
	(-20.1)	(-15.3)	(3.4)	(-7.7)	(-9.3)**	(-4.8)*	(-1.8)*	(7.3)	(2.3)
BA-119 × AZ-31	10.8	6.7	39.7	4872	29.4	31.8	85.8	4.88	5.37
	(6.9)	(6.2)	(1.8)	(7.3)	(-0.4)	(-4.2)	(1.1)	(5.6)	(0.6)
BA-119 × DPL-90	9.5	8.1	39.8	3827	29.1	31.7	85.0	4.91	6.17
	(-5.8)	(35.2)**	(-1.8)	(12.1)	(0.5)	(0.4)	(0.8)	(3.4)	(3.6)
$LSD_{(0.05)}$	2.32	1.24	2.03	829.4	1.87	1.95	1.91	0.46	0.51
S.E.(Heterosis)	1.056	0.481	0.807	48.93	0.623	0.707	0.721	0.186	0.209

Upper and lover values denote mean performance and heterosis, respectively

Discussion

Significant genetic diversity among the investigated traits for parental lines/testers and their crosses demonstrates the existence of variability. The detected significant mean square values of parental cultivars and crosses for all the traits suggested the existence of non-additive gene action and high heterotic response. The lowest ratios of σ2GCA/σ2SCA also indicated predominance of non-additive gene action and were found responsible for inheritance of these traits (Sprague and Tatum, 1942). Results showed that heterosis breeding would be suitable for investigated characters.

The line Carmen was best general combiner for fiber quality parameters but didn’t show better performance for yield components. However, among testers, the Tamcot-22 was good general combiner not only for yield and lint percentage, but also for fiber length and fiber elongation. Generally, the general combiners among lines and testers exhibited better mean performance as reflected by positive association between them indicating that the parent may be selected either on the basis of GCA or mean performance or in combination. The positive GCA effects indicated that continued progress should be positive through breeding yield, its components and fiber quality traits. Similar conclusions were also made by Tang *et al.,* (1993), Meredith & Brown (1998) and Ahuja & Dhayal (2007). The SCA effects showed that the best specific combinations were not always obtained from parents with desirable GCA effects. These findings were inconsistent with some previous studies reported by Khan *et al.,* (1991), Coyle & Smith (1997), Shakeel *et al.,* (2001), Basal & Turgut (2003). However, Khan *et al.,* (2007) and Basal *et al.,* (2009) reported that higher GCA of parents does not necessarily confer higher SCA, thus GCA and SCA were independent.

Specific combining ability effects represent the deviation of hybrid performance from the estimated GCA effects for each parent. The GCA effects of parents did not confer high and significant SCA effects for hybrids. Also, the crosses with high SCA produced best cross combinations i.e., Sahin 2000 × NIAB-999 for yield, GSN 12 × NIAB-999 for boll number and BA 119 × DPL-90 for boll weight. However, some crosses with high SCA even were not able to show good mean performance i.e. BA 119 × AZ-31, BA 119 × DPL-90 for yield and Sahin 2000 × SJ-U86 for boll number. Results also revealed that good SCA effects didn’t necessarily indicate superior trait performance. In F_1 crosses, the highest heterosis values for yield, boll number, boll weight and lint percentage were 79.8, 19.8, 35.2, and 5.7%, respectively. The observed heterotic values especially for yield were higher than previous studies (Meredith, 1998, Campbell *et al*., 2008). Results also manifested that parents from different regions of the world may produce high heterosis. The estimated maximum heterosis was 9.6% for fiber length, 9.9% for fiber strength, 2.7% for uniformity index, 14.1% for micronaire and 4.9% for elongation. Heterosis values for fiber quality parameters were generally lower than that for yield components, which is consistent with previous findings (Luckett, 1989; Meredith and Brown, 1998).

The F_1 hybrids i.e. Sahin-2000 × Tamcot-22, Sahin-2000 × NIAB-999, Carmen × Tamcot-22, and Carmen × NIAB-999 were noticed as high yielding F_1 hybrids with desirable fiber quality parameters. Among these crosses, only Sahin-2000 × NIAB-999 had positive and significant SCA effect. Sahin-2000 and Tamcot-22 showed significant GCA effects for seed cotton yield. NIAB-999 exhibited high but non-significant GCA effects for yield, however mean performance of NIAB-999 for seed cotton yield was high. Among these parents, Carmen was the best general combiner for improving fiber quality as defined by increased length, improved strength, uniformity index, and decreased fiber diameter i.e. lower micronaire. Results authenticated that selection of best cross combinations should be based on GCA, SCA, mean performance and or in combination.

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