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Combining ability for fiber quality parameters and within-boll yield components in intraspecific and interspecific cotton populations

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Abstract

The major problem with the simultaneous improvement of yield with higher fiber quality is the negative association due to the linkage and pleiotropic effects between lint yield components and fiber quality parameters. The objectives of this research were to estimate the general combining ability (GCA) of parents and specific combining abilities (SCA) of hybrids for fiber quality parameters and within-boll yield components, and to determine the association of fiber quality parameters with basic within-boll lint yield components. In this study, eight cotton cultivars and 15 F_1 hybrids obtained by crossing five lines and three testers in the line × tester mating system during 2006 were planted in a randomized block design with four replications in 2007. The predominance of non-additive gene action was estimated for all traits except for the upper half mean fiber length (UHM), fiber strength, and seeds per boll, which were controlled by an additive type gene action due to the high GCA variance. Among the parents, 'Askabat-100' and 'Carmen' were the best general combiners for fiber length, strength, and uniformity index (UI). Additionally, 'GW Teks' and 'Sahin-2000' were determined to be good combiners for lint weight per seed (L/S) and spinnable fibers per seed (F/S). The SCA effects showed that the best specific combination was 'Sealand-542' × 'Sahin-2000' and 'TAM 94L-25' × 'SG-125' for lint percentage, L/S, and lint weight unit per seed surface area. The most important fiber quality parameters, UHM, fiber strength, and UI, were negatively associated with the most basic within-boll lint yield components, L/S, and F/S.

Additional keywords: gene action, general and specific combining ability, *Gossypium* sp., line × tester.

Resumen

Aptitud combinatoria para parámetros de calidad de fibra y los componentes de producción de cápsulas en poblaciones intraespecíficas e interespecíficas de algodón

El principal problema para la mejora simultánea de la producción y la obtención de fibra de alta calidad en el algodón es la asociación negativa entre la producción de fibra y los parámetros de calidad de la misma debido al ligamiento y los efectos pleitrópicos. Los objetivos de este trabajo fueron estimar la aptitud combinatoria general (GCA) de los parentales y la aptitud combinatoria específica (SCA) de los híbridos para los parámetros de calidad de fibra y los componentes de producción de la cápsula del algodón, así como determinar la asociación entre los parámetros de calidad de fibra con componentes básicos de producción de fibra. En este estudio, se plantaron ocho cultivares de algodón y 15 híbridos F_1 en 2007, en un diseño de bloques al azar con cuatro repeticiones. Los híbridos F1 fueron obtenidos en 2006 por cruzamientos de 5 líneas y 3 testigos mediante un sistema de cruce línea × testigo. Se estimó la predominancia de la acción génica no aditiva para todos los caracteres excepto para la longitud de la mitad superior de la fibra (UHM), resistencia de la fibra y semillas por cápsula, que fueron controlados por una acción génica de tipo aditivo debido a una varianza GCA alta. Entre los parentales, 'Askabat-100' y 'Carmen' fueron los que presentaron la mejor aptitud GCA para longitud de fibra, resistencia e índice de uniformidad (UI). Además, se determinó que 'GW Teks' y 'Sahin-2000' presentaron una buena aptitud combinatoria general para peso de fibra por semilla (L/S) y fibras por semilla (F/S). Los efectos SCA mostraron que las mejores combinaciones específicas fueron los cruces: 'Sealand-542' × 'Sahin-2000' y 'TAM 94L-25' × 'SG-125' para porcentaje de fibra, L/S, y unidad de peso de fibra por área de superficie de semilla. Los parámetros de calidad de fibra más importantes (UHM, resistencia de fibra y UI) estaban negativamente asociados con la mayoría de los componentes básicos de producción de fibra en cápsula (L/S y F/S).

Palabras clave adicionales: acción génica, aptitud combinatoria general y específica, *Gossypium* sp., línea × testigo.

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Introduction

Breeding programs continue to develop new cotton varieties to meet the requirements of both producers and consumers. High fiber quality is important for the textile industry since fiber quality directly affects processing performance, productivity, yarn quality, and the marketing of textile properties. New spinning and weaving technologies in the textile industry mandate that plant breeders and geneticists develop cultivars of upland cotton with improved fiber quality, especially fiber strength, fiber length, and length uniformity without sacrificing yield potential. However, previous studies report that the negative association resulting from the linkage connections and pleiotropic effects between lint yield and fiber quality, and especially between yield and fiber strength, has hampered the simultaneous improvement of these two important characteristics in cotton (Scholl and Miller, 1976; Worley *et al.,* 1976; Culp *et al.,* 1979; Green and Culp, 1990; Basal and Smith, 1997; Smith and Coyle, 1997). In cotton, increasing one of the yield components often results in decreasing other fiber quality component(s) because of balanced compensation. A number of breeding methods have been proposed to overcome the negative correlations between fiber quality parameters and lint yield components (Jensen, 1970; Meredith and Bridge, 1971; Basal and Smith, 1997; Coyle and Smith, 1997; Basal and Turgut, 2003; Herring *et al.,* 2004; Ahuja and Dhayal, 2007).

The knowledge of an investigated trait's gene action would enable breeders to determine more efficient selection methods and genetic populations. The choice of selection and breeding procedures to improve cotton or any other crop genetically largely depends on the knowledge of the plant material's type, the proportions of its genetic components and the presence of non-allelic interactions of different characteristics (Esmail, 2007). When the additive effects are larger than the non-additive ones, selection in early segregating generations would be effective; however, if the non-additive portions are larger than the additive ones, the improvements of the characteristics need intensive selection through later generations (Jagtap, 1986). Single plant selection in early generations would effectively improve the seed cotton yield and its various additively controlled components (Saeed *et al.,* 2000; Azhar and Khan, 2005; Ali *et al.,* 2008). The relative importance of the non-additive effects suggests that selection should be applied in advanced generations of the breeding program. Moreover, simple selection in top performing hybrids can also be studied by further segregating generations (Saeed *et al.,* 2000; Cruz *et al.,* 2006; Khan *et al.,* 2009). Previous studies show that yield and yield components were influenced by non-additive (Shakeel *et al.,* 2001; Ahuja and Dhayal, 2007) and some researchers found that both additive and non-additive gene effects influenced yield and yield components. (Kumaresan *et al.,* 1999; Basal and Turgut, 2005) gene effects. Hassan *et al.* (2000) and Ahuja and Dhayal (2007) report a non-additive gene action for fiber quality parameters. Cheatham *et al.* (2003) indicate that the lint percentage and fiber strength exhibited primarily additive gene effects, while micronaire and length exhibited primarily dominant genetic effects. A number of researchers reported significant general combining ability (GCA) for basic yield components and fiber quality parameters (Green and Culp, 1990; Coyle and Smith, 1997; Basal and Turgut, 2003; Ahuja and Dhayal, 2007).

Yield, within-boll yield components, and fiber quality parameters are quantitatively inherited; the phenotype of each trait is influenced by the genotype, the environment and the interaction of genotype with environment. To overcome this phenomenon, the first step is to select the appropriate parents and hybridize the selected parents to produce large populations of progeny. Then these populations can be evaluated based on traits of interest to select individuals and/or families. The line x tester analysis is commonly used to analyze combining ability, the breeding value of parental lines to produce hybrids, in plant breeding by a simple extension and application of the analysis. In order to choose the appropriate parents and crosses and to estimate the combining abilities of parents in the early generation,

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Abbreviations used: BW (boll weight), CM (converted micronaire), df (degree of freedom), F/S (spinnable fibers seed^{-1}), F/SAS (spinnable fibers unit seed surface area), GCA (general combining ability), HVI (high volume instrument), L/S (lint weight seed^{-1}), L/SAS (lint weight unit seed surface area), LC/S (lint cotton seed^{-1}), LP (lint percent), LP (lint percent), Mic. (micronaire), ML (mean fiber length), S/B (seeds boll^{-1}), SAS (surface area seed^{-1}), SC/S (seed cotton seed^{-1}), SCA (specific combining ability), SCW/B (seed cotton weight boll^{-1}), SE (standard error), Str. (fiber bundle strength), UHM (upper half mean fiber length), UI (fiber length uniformity index), σ^2 A (additive genetic variance), σ^2 D (non-additive genetic variance), σ^2 GCA (general combining ability variance), σ^2 SCA (specific combining ability variance).

the line × tester analysis method has been widely used in self- and cross-pollinated plants by plant breeders (Konak *et al.,* 1999; Mert *et al.,* 2003; Ahuja and Dhayal, 2007; Basbag *et al.,* 2007). Sprague and Tatum (1942) used the term "general combining ability" (GCA) to designate the average performance of a line in hybrid combinations, and they used the term "specific combining ability" (SCA) to define those cases in which certain combinations perform relatively better or worse than expected on the basis of the average performance of the lines involved. The objectives of this research were (i) to estimate the general and specific combining abilities for fiber quality parameters and within-boll yield components among a group of cotton genotypes that varied by investigated traits; (ii) to identify the appropriate parents and crosses for the investigated traits; and (iii) to determine the association of fiber quality parameters with basic within-boll lint yield components among eight diverse cotton genotypes and their intraspecific and interspecific F_1 cotton populations developed by line tester mating system.

Material and methods

The genetic population was developed by crossing five cotton varieties (female/lines), including 'Askabat 100', 'Aydin 110', 'Sealand 542', 'GW Teks', and 'TAM 94L-25', with three cotton varieties (male/tester), including 'Carmen', 'Sahin-2000', and 'SG-125', in a line × tester mating design. Askabat 100 is a *Gossypium barbadense* L. variety with extra long stable and finest fiber characteristics. Sealand 542 and Aydin-110 were developed through interspecific hybridization (*Gossypium hirsutum* L. × *Gossypium barbadense* L.) and have long stable and finest fiber characteristics. GW Teks (*G. hirsutum*) has fiber superior strength. TAM 94L-25 (*G. hirsutum*) is an early-fruiting upland cotton line that has superior fiber length and strength even under dryland conditions (Smith, 2003). Carmen, Sahin-2000, and SG-125 (*G. hirsutum*) have acceptable fiber properties with high yield potential and are well-adapted current commercial cotton varieties.

Five female (lines) and three male (testers) cotton varieties were hand crossed using the line × tester method in 2006. The parents and their intraspecific and interspecific F_1 cotton populations were grown in 2007 in the experimental fields of Adnan Menderes University Agriculture Faculty. Each genotype was planted in a single 6 m long row in a randomized block design with 4 replications. The distances between and within the rows were 0.70 m and 0.20 m, respectively. Twenty well-developed open bolls were hand harvested randomly from each row of parents and F_1's. The bulked bolls from each genotype were ginned on a laboratory roller gin. The seed cotton weight per boll (SCW/B) and lint percentage (LP) were obtained from each boll sample. A high volume instrument (HVI) was used to measure micronaire (Mic.) fiber length (UHM), uniformity, fiber strength, elongation, and short fiber index. After a seed index was obtained, the seeds were delinted with concentrated sulfuric acid. The seed volume was determined by the volumetric displacement of 100 delinted seeds in 13 mL of ethyl alcohol. The estimation of the seed surface area was performed using Hodson's (1920) estimation table. Within-boll yield components were calculated by the ontogenetic yield model of Worley *et al.* (1976), which is also reported in Basal and Smith (1997). These components were as follows: boll weight (BW), seed cotton weight per sample/number of bolls in the sample; lint percent (LP), 100 x sample lint weight/sample seed cotton weight; seed index, weight of 100 fuzzy seeds; seeds/boll (S/B), BW·(1-LP/100/seed index/100); converted micronaire (CM), HVI micronaire·$39.36 \cdot 10^{-6}$ (converts HVI micronaire to g m^1); mean fiber length (ML), UI·UHM·10^{-3} (converts units from mm to m); surface area per seed (SAS), estimated from Hodson's (1920) table; seed cotton per seed (SC/S), BW/(S/B); lint cotton/seed (LC/S), (SC/S)·(LP/100); spinnable fibers / seed (F/S), (LC/S)/(ML·CM); and spinnable fibers per unit seed surface area (F/SAS), (F/S)/(SA/S). To determine lint weight components in the same manner as the fiber number components, lint weight per seed was calculated as L/S = = (F/S)·(ML)·(CM). Likewise, lint weight per unit seed surface area was determined as (L/SAS) = = (F/SAS)·(ML)·(CM).

The GCA effects of the parents and the SCA effects of the hybrids were estimated using the line × tester analyses method described by Kempthorne (1957). Correlations of fiber quality parameters and within-boll lint yield components were determined using SAS procedures (SAS Institute, 1999) for each of two sets of data, including the parents and the 15 F_1 populations.

Results

Significant differences were detected among parents and hybrids in both fiber quality parameters and within-boll yield components, thus indicating the presence of genetic diversity among them (Table 1). These data indicate that the parents or crosses do not follow the same pattern for investigated traits. The ratio of σ^2 GCA/σ^2 SCA was less than zero for fiber length UI, Micronaire (Mic.), lint percent (LP), surface area/seed (SAS); lint weight/seed (L/S), lint weight / unit seed surface area (L/SAS), spinnable fibers/seed (F/S), and spinnable fibers/unit seed surface area (F/SAS). GCA variances were higher than SCA variances for upper half mean fiber length (UHM), fiber bundle strength (Str.) and seeds/boll (S/B), which indicates additive gene action for these traits.

The proportional contributions of the lines (females) and testers (males) and their interactions to the total variance for investigated characteristics are presented in Table 2. These results reveal that the maximum contribution to the total variance of all traits was made by female parents. Furthermore, the contribution of the line × tester interactions was higher than that of the males for all of the investigated characteristics, except the fiber strength and uniformity index. The maximum contributions to the total variance for most of the characteristics under study were made by the female (line) parents and the line × tester interactions (Table 2).

The eight parents used in this study varied significantly for each of the evaluated fiber quality parameters and within-boll yield components (Table 3). Askabat 100 exhibited the longest fibers (33.3 mm UHM length), while SG-125 had the shortest UHM length at only 28.8 mm. Among the parents, GW Teks, Aydin 110, and Askabat 100 had the strongest fibers, ranging from 35.8 to 34.4 g/tex, and Sahin-2000 had the weakest fibers, 27.6 g/tex. Length uniformity, *i.e.*, UI, was expected and showed little meaningful variation. Carmen and SG-125 had the highest micronaire and lint percentage values. The *G. hirsutum* cultivars generally had more seed than developed through interspecific hybridization *G. hirsutum* × *G. barbadense* cultivars and *G. barbadense* cultivars in terms of the number of seeds per boll. These variations in fiber quality parameters and boll properties were as predicted for these particular parents and supported their selection as parents for this study. Parents separated from each other for the within-boll yield components as expected. Askabat 100 contributed smaller seeds, less lint weight/seed, less lint weight/unit seed surface area, fewer spinnable fibers/seed, and fewer spinnable fibers/unit seed surface area (Table 3). Sealand 542 had the largest seeds (1.2679 cm^2); however, it produced less L/S, L/SAS, F/S, and F/SAS. GW Teks produced higher lint weight/seed and/or more fibers/seed than all the other genotypes used in this study. These data indicate that the maximization of within-boll lint yield components does not follow the same pattern in every genotype.

Table 1. Analysis of variance for fiber quality parameters and within-boll yield components of eight parents and 15 F_1 hybrids

Source of variation	df	UHM[1]	Str	UI	Mic.	LP	S/B	SAS	L/S	L/SAS	F/S	F/SAS
Replication	3	0.33	2.9	1.9	0.09*	0.40	27.1**	0.001	3.5	7.8	2882**	2991**
Genotypes	22	17.3**	27.1**	3.4**	0.64**	23.1**	59.9**	0.015**	323**	185**	10406**	5156**
Parents	7	9.3**	30.5**	2.4*	0.58**	37.1**	67.9**	0.032**	458**	256**	17665**	8423**
Parents *vs.* Hybrids	1	5.9**	18.7*	15.5**	0.22**	44.9**	61.3**	0.024**	1307**	549**	21504**	5065**
Hybrids	14	22.1**	26**	3.0**	0.70**	14.5**	55.8**	0.005**	186**	123**	5984**	3529**
Females	4	75.2**	64.6**	6.8**	2.13**	42.0**	167**	0.010*	555**	349**	15978**	9470**
Males	2	1.32	43.8**	5.7**	0.07	3.8	19.2	0.005	41	24	4651	1267
Females × Males	8	0.81	2.2	0.48	0.14**	3.4**	9.4	0.030**	38**	35**	1321	1123*
Error	66	0.628	2.684	0.91	0.024	0.37	4.9	0.001	3.7	3.3	700	516
σ^2 GCA[2]		0.565	0.630	0.068	0.015	0.294	1.232	0.001	3.938	2.340	123	63
σ^2 SCA		0.044	0.113	0.109	0.028	0.762	1.110	0.002	8.553	7.998	155	151
σ^2 GCA / σ^2 SCA		12.84	5.575	0.623	0.535	0.386	1.110	0.50	0.460	0.293	0.797	0.419
σ^2 A		1.130	1.261	0.136	0.030	0.588	2.464	0.002	7.876	4.680	246	127
σ^2 D		0.044	0.113	0.109	0.028	0.762	1.110	0.002	8.553	7.998	155	151

[1] UHM: Upper half mean fiber length; Str: Fiber bundle strength; UI: Fiber length uniformity index; Mic.: Micronaire; LP: Lint percent; S/B: seeds $boll^{-1}$; SAS: Surface area $seed^{-1}$; L/S: Lint weight $seed^{-1}$; L/SAS: Lint weight per unit seed surface area; F/S: Spinnable fibers $seed^{-1}$; F/SAS: Spinnable fibers per unit seed surface area. *, ** Significant at 0.05 and 0.01% levels, respectively. [2] σ^2 GCA: general combining ability variance; σ^2 SCA: specific combining ability variance; σ^2 A: additive genetic variance; σ^2 D: non-additive genetic variance.

Table 2. Proportional contributions of lines, testers and their interaction to total variances for the investigated characters

Source of variation	df	UHM[1] (mm)	Str (g/tex)	UI (%)	Mic. (µg/inch)	LP (%)	S/B (No.)	SAS (cm^2)	L/S (mg)	L/SAS (mg)	F/S (x1000)	F/SAS x1000
Females	4	97.07	71.03	64.30	87.41	82.74	85.50	57.08	84.08	80.86	76.28	76.67
Males	2	0.85	24.07	26.75	1.45	3.81	4.91	15.00	2.95	2.82	11.10	5.13
Lines × Testers	8	2.08	4.90	8.95	11.14	13.45	9.59	27.92	12.97	16.32	12.62	18.20
Error	66	0.628	1.921	0.91	0.024	0.37	4.9	0.001	3.7	3.3	700	516

[1] See Table 1.

Significant GCA effects were detected for each fiber quality trait and within-boll yield component evaluated (Table 4). The estimated GCA effect for the eight parents significantly varied for both fiber quality traits and within-boll yield components. Among these genotypes, Askabat-100 was the best general combiner for improving fiber quality as defined by improved strength, increased length, uniformity index, and decreased fiber diameter, *i.e.*, lower micronaire (Table 4). Carmen also was good combiner for fiber strength and uniformity index. Aydin-110, GW Teks, and Carmen were determined to be good combiners for the lint percentage. In terms of within-boll yield components among the parents, the best general combiner was Aydin-100 for L/S and L/SAS, Sealand-542 for S/B, GW Teks for S/B, L/S, L/SAS, F/S, and F/SAS, TAM 94L-25 for S/B, Carmen for S/B, and Sahin-2000 for SAS, L/S, and F/S.

The SCA effects showed that the best specific combinations were TAM 94L-25 × Sahin-2000 and Aydin-110 × Carmen for Mic.; Sealand-542 × Sahin-2000 and TAM 94L-25 × SG-125 for lint percentage; TAM 94L-25 × Sahin-2000 for surface area/seed; TAM 94L-25 × SG-125 and Askabat-100 × Carmen for lint weight/seed; and TAM 94L-25 × SG-125, Sealand-542 × Sahin-2000, and Aydin-110 × SG-125 for lint weight / unit seed surface area (Table 5). Some of these crosses were related to their parents' GCA effects; at least one of their parents had high or average GCA effects for particular traits. However, some of the best specific combinations (Askabat-100 × Carmen for lint weight/seed, TAM 94L-25 × SG-125 for lint percentage, lint weight/seed, and lint weight/unit seed surface area) were obtained from parents having poor and negative GCA effects.

The mean performance and heterosis values of the fiber characteristics and within-boll yield components of 15 F_1 hybrids are presented in Table 6. The majority of the crosses produced higher values for investigated traits than their parents. Due to the interspecific hybridization, Askabat-100 × Carmen, Askabat-100 × Sahin-2000, and Askabat-100 × SG-125 hybrids have higher heterotic effects for all traits than the rest of the hybrids, except for L/P, S/B, L/S, and F/SAS. Sealand-542 × Sahin-2000 for L/P, L/SAS, and F/SAS and

Table 3. Mean performance of fiber quality parameters and within-boll yield components of eight parents

Parents	UHM[1] (mm)	Str (g/tex)	UI (%)	Mic. (µg/inch)	LP (%)	S/B (No.)	SAS (cm^2)	L/S (mg)	L/SAS (mg)	F/S (x1000)	F/SAS (x1000)
Askabat 100	33.3 a[2]	34.4 ab	84.9ab	3.7d	33.7d	18.9f	0.9873e	47.3f	47.9f	11.4e	11.6de
Aydin 110	31.1 b	35.1a	83.8bc	4.2bc	35.6c	26.3c	1.2082b	67.3cd	55.7d	15.5bc	12.8cd
Sealand 542	31.7 b	31.0cd	83.3c	4.3bc	32.7d	22.2e	1.2679a	64.6d	50.9e	14.4cd	11.4e
GW Teks	29.7 cd	35.8a	85.6a	4.4b	39.9a	24.8cd	1.2082b	82.7a	68.4a	18.5a	15.3a
TAM 94L-25	30.8 bc	32.6bc	84.5abc	4.1c	32.8d	31.8a	1.1332c	55.7e	49.2ef	13.3d	11.8de
Carmen	29.2 d	31.8cd	84.7abc	4.9a	39.1a	29.2b	1.1168c	72.6b	65.0b	15.2bc	13.6bc
Sahin-2000	29.3 d	27.6e	84.1abc	4.3bc	37.2b	24.1de	1.1503c	69.9bc	60.8c	16.6b	14.4ab
SG-125	28.8 d	30.1d	85.3a	4.8a	39.6a	28.4b	1.0558d	68.6c	65.1b	14.8cd	14.0abc
LSD (0.05)	1.282	2.458	1.516	0.275	1.068	2.059	0.039	3.635	2.801	1637	1329

[1] See Table 1. [2]: Values within columns followed by same letter are not different at *P*: 0.05 level.

Table 4. General combining ability effects for fiber quality parameters and within-boll yield components of eight parents

Parents	UHM[1] (mm)	Str (g/tex)	UI (%)	Mic. (µg/inch)	LP (%)	S/B (No.)	SAS (cm^2)	L/S (mg)	L/SAS (mg)	F/S (x1000)	F/SAS (x1000)
Females											
Askabat-100	4.42**	3.108**	0.78**	-0.71**	-2.05**	-6.56**	0.027**	-2.91**	-3.87**	-255	-502*
Aydin-110	-0.87**	0.375	-0.38	0.35**	1.11**	0.88	0.015	4.12**	2.67**	121	-62
Sealand-542	-1.25**	-3.133**	-0.87**	0.08	-0.53**	1.37*	0.012	-1.59**	-1.92**	92	-46
GW Teks	-1.66**	0.792	0.80**	0.28**	2.63**	1.59*	-0.007	9.05**	8.12**	1626**	1470**
Tam 94L-25	-0.65 *	-1.142**	-0.32	0.012	-1.16**	2.72**	-0.047**	-8.68**	-4.99**	-1614**	-858**
Males											
Carmen	0.23	1.570**	0.46*	0.043	0.35*	1.13*	-0.019*	-0.50	0.53	-467*	-186
Sahin-2000	-0.28	-1.370**	-0.58**	0.026	0.15	-0.61	0.013*	1.63**	0.74	495*	286
SG-125	0.046	-0.200	0.118	-0.068	-0.49**	-0.52	0.006	-1.12**	-1.27**	-27	-99
SE (Females)	0.229	0.473	0.275	0.045	0.175	0.641	0.008	0.555	0.524	241	207
SE (Males)	0.177	0.366	0.213	0.035	0.136	0.496	0.006	0.430	0.406	187	160

[1] See Table 1. *, ** Significant at 0.05 and 0.01% levels, respectively. SE: standard error.

Sealand-542 × Carmen for S/B exhibited better heterosis among the 15 crosses (Table 6). Additionally, intraspecific crosses showed low heterosis for the investigated traits. Generally, crosses with higher heterosis values have either a positive SCA or high mean performance.

A negative and significant association was found between fiber length and LP, L/S, L/SAS, and F/SAS for both intraspecific and interspecific hybridization (Table 7). Unlike intraspecific hybridization, S/B was negatively associated with UHM and fiber strength. On the other hand, a positive and significant correlation was found between fiber strength and LP in intraspecific hybridization population. The fiber length uniformity index was negatively associated with F/S and F/SAS and positively correlated with SAS in interspecific hybridization. Micronaire was positively associated with LP, L/S, and L/SAS for both hybridization populations and S/B among the interspecific crosses, as one would expect. Higher lint percent (LP) was positively

Table 5. Specific combining ability effects for fiber quality parameters and within-boll yield components of 15 F_1

Crosses	UHM[1] (mm)	Str (g/tex)	UI (%)	Mic. (µg/inch)	LP (%)	S/B (No.)	SAS (cm^2)	L/S (mg)	L/SAS (mg)	F/S (x1000)	F/SAS (x1000)
Askabat-100 × Carmen	0.36	-1.103	0.26	0.08	0.31	-0.34	0.014	2.60**	1.43	135	-45
Askabat-100 × Sahin-2000	0.28	0.637	-0.27	0.06	0.41	0.52	0.008	1.15	0.70	-74	-143
Askabat-100 × SG-125	-0.43	0.467	0.007	-0.14	-0.75*	-0.19	-0.022	-3.75**	-2.13*	-60	188
Aydin-110 × Carmen	0.48	0.180	0.28	-0.16*	-0.68*	-1.95	0.025	-2.95**	-3.74**	-361	-575
Aydin-110 × Sahin-2000	-0.66	-0.180	0.22	0.06	0.03	2.38*	-0.005	1.00	1.06	307	307
Aydin-110 × SG-125	0.18	-0.001	-0.50	0.09	0.17	-0.45	-0.019	1.95*	2.67**	54	267
Sealand-542 × Carmen	-0.12	0.263	0.04	0.01	-0.01	1.53	-0.007	0.50	0.72	120	167
Sealand-542 × Sahin-2000	-0.24	-0.297	-0.11	0.09	1.08**	-0.79	-0.016	2.35*	2.76**	393	511
Sealand-542 × SG-125	0.35	0.033	0.06	-0.10	-1.07**	-0.74	0.023	-2.85**	-3.48**	-514	-679
GW Teks × Carmen	-0.29	0.838	-0.08	-0.03	0.36	-0.36	0.006	0.88	0.55	422	312
GW Teks × Sahin-2000	0.48	0.228	-0.04	0.11	-0.30	-0.54	-0.012	-1.94*	-1.01	-1046*	-756*
GW Teks × SG-125	-0.19	-1.067	0.12	-0.08	0.05	0.89	0.006	1.06	0.46	624	444
TAM 94L-25 × Carmen	-0.23	-0.178	-0.51	0.09	0.12	1.11	-0.038**	-1.02	1.04	-316	141
TAM 94L-25 × Sahin-2000	0.140	-0.388	0.19	-0.33**	-1.18**	-1.58	0.026*	-2.57**	-3.51**	420	80
TAM 94L-25 × SG-125	0.089	0.567	0.32	0.23	1.06**	0.47	0.012	3.59**	2.47**	-103	-221
SE	0.396	0.819	0.477	0.077	0.303	1.110	0.013	0.962	0.908	418	359

[1] See Table 1. *, ** Significant at 0.05 and 0.01% levels, respectively.

Table 6. Mean performance and heterosis of fiber characteristics and within-boll yield components of 15 F_1 hybrids

Crosses	UHM [1] (mm)	Str (g/tex)	UI (%)	Mic. (µg/inch)	LP (%)	S/B (No.)	SAS (cm^2)	L/S (mg)	L/SAS (mg)	F/S (x1000)	F/SAS (x1000)
Askabat-100 × Carmen	35.83a [2] (14.7) [3]	36.8a (11.2)	86.8a (2.4)	3.86f (-10.3)	36.4ef (-0.1)	21.67d (-9.8)	1.1989abc (13.9)	73.20ef (22.1)	61.10de (8.2)	15.4d (15.9)	12.9ef (2.3)
Askabat-100 × Sahin-2000	35.44a (13.3)	35.6ab (15.2)	85.3bcd (0.9)	3.83f (-4.9)	36.3fg (2.4)	20.79d (-3.5)	1.2227a (14.4)	73.88ef (26.1)	60.47de (11.3)	16.2cd (15.4)	13.3def (1.9)
Askabat-100 × SG-125	35.06a (12.9)	36.6a (13.2)	86.3abc (1.4)	3.54g (16.8)	34.5h (-5.9)	20.16d (-14.9)	1.1878abcd (16.3)	66.23gh (14.2)	55.74f (-1.3)	15.7d (19.7)	13.2def (3.2)
Aydin-110 × Carmen	30.87b (2.6)	35.4ab (5.9)	85.8abcd (1.8)	4.69bcd (2.7)	38.6c (3.3)	27.50c (-1.7)	1.1959abc (2.9)	74.68de (6.9)	62.47cd (3.6)	15.3d (-0.2)	12.8ef (-2.9)
Aydin-110 × Sahin-2000	29.22f (-3.2)	32.1cde (2.4)	84.7de (0.9)	4.89a (14.4)	39.0c (7.3)	30.10abc (19.4)	1.1972abc (1.5)	80.76bc (17.7)	67.47b (15.9)	16.9bc (5.4)	14.2bc (3.7)
Aydin-110 × SG-125	30.38bc (1.6)	33.4bc (2.5)	84.6de (0.1)	4.83abc (7.0)	39.1c (4.1)	27.36c (0.1)	1.1778bcde (4.1)	78.96c (16.2)	67.08b (11.2)	16.2cd (6.7)	13.7cd (2.4)
Sealand-542 × Carmen	29.89cdef (-1.8)	32.0cde (1.9)	85.0cde (1.2)	4.59d (-0.4)	37.6d (4.7)	31.46ab (22.9)	1.1616cde (-2.5)	72.42f (5.6)	62.34cd (7.6)	15.8d (6.4)	13.6cde (8.6)
Sealand-542 × Sahin-2000	29.26ef (-4.1)	28.5f (-2.8)	83.8e (0.2)	4.65cd (7.7)	38.5c (10.2)	27.41c (18.3)	1.1833bcde (-2.1)	76.39d (13.6)	64.59c (15.6)	17.0bc (9.8)	14.4bc (11.5)
Sealand-542 × SG-125	30.18bcde (-0.2)	30.0ef (-2.0)	84.7de (0.5)	4.37e (-4.0)	35.7fg (-1.2)	27.55c (9.2)	1.2154ab (4.7)	68.44g (2.8)	56.35f (-2.8)	15.6d (6.8)	12.8ef (1.0)
GW Teks × Carmen	29.30def (-0.5)	36.5a (8.1)	86.6ab (1.7)	4.74abcd (1.3)	41.0a (3.9)	29.81abc (10.6)	1.1556de (-0.6)	83.43a (7.5)	72.20a (8.3)	17.6ab (4.2)	15.2a (5.2)
GW Teks × Sahin-2000	29.57cdef (0.2)	32.9c (3.9)	85.6abcd (0.8)	4.87ab (10.8)	40.3b (4.5)	27.89bc (14.4)	1.1687cde (-0.9)	82.75ab (8.4)	70.85a (9.6)	17.1bc (-2.7)	14.6ab (-1.7)
GW Teks × SG-125	29.22f (-0.1)	32.8c (-0.4)	86.4ab (1.1)	4.58d (-1.0)	40.0b (0.6)	29.40abc (10.5)	1.1805bcde (4.3)	83.00ab (9.7)	70.31a (5.4)	18.2a (9.5)	15.5a (5.3)
TAM 94L-25 × Carmen	30.37bc (1.3)	33.5bc (3.9)	85.0cde (0.5)	4.61d (2.7)	37.1de (3.1)	32.40a (6.5)	1.0711f (-4.8)	63.80i (-0.4)	59.59e (4.5)	13.6e (-4.2)	12.7f (0.6)
TAM 94L-25 × Sahin-2000	30.23bcd (0.6)	30.4def (0.8)	84.7de (0.5)	4.17e (-0.8)	35.6g (1.7)	27.98bc (-0.4)	1.1656cde (2.1)	64.38hi (2.5)	55.24f (0.5)	15.3d (2.2)	13.1def (0.2)
TAM 94L-25 × SG-125	30.50bc (2.4)	32.5cd (3.6)	85.5bcd (0.7)	4.63cd (4.4)	37.2d (2.7)	30.11abc (0.1)	1.1455e (4.7)	67.79g (9.0)	59.22e (3.7)	14.3e (1.5)	12.4f (-3.3)
LSD (0.05)	0.956	2.349	1.315	0.201	0.733	3.698	0.039	2.245	2.401	944.4	834.6

[1] See Table 1. [2]: Values within columns followed by same letter are not different at *P*: 0.05 level. [3]: % heterosis value of crosses.

associated with higher L/S, L/SAS, F/S, and F/SAS for both cross populations.

Discussion

Significant genetic diversity among the investigated traits in the parents and crosses demonstrates the existence of variability. The detected significant mean square value of parents versus hybrids in all of the investigated traits suggests the existence of non-additive gene action and high heterotic responses for the traits. The lower ratio of σ^2 GCA / σ^2 SCA indicates a predominance of non-additive gene action (dominant or epistasis) in the inheritance of traits (Sprague and Tatum, 1942). While UHM, fiber bundle strength (Str.) and seeds/boll (S/B) were controlled by additive gene action, the rest of the traits exhibited non-additive gene action. Previous studies show that variation in seed cotton yield and its components was controlled by genes acting either additively or non-additively. Non-additive gene action for fiber quality traits, including fiber length, fiber strength and micronaire value, have been reported by Khan *et al.* (1991), Baloch *et al.* (1997) and Hassan *et al.* (2000). Cheatham *et al.* (2003) indicated that lint percentage and fiber strength exhibited primarily additive genetic effects, while micronaire and length exhibited primarily dominant genetic effects. The result of the half-diallel analysis showed that LP exhibited additive and dominant genetic effects, with the dominant effect being primary. Fiber strength had approximately equal additive and dominant genetic effects (Basal and Turgut, 2005). Ahuja and Dhayal (2007) reported non-additive gene action for seed cotton yield per plant and the majority of its component traits including fiber traits. Contradictory results could result from the cultivars having different genetic backgrounds or environmental conditions during growth. They could

Table 7. Correlations of fiber quality parameters with within-boll lint yield components for intraspecific and interspecific F[1] cotton populations

	LP		S/B		SAS		L/S		L/SAS		F/S		F/SAS	
	Intra-specific	**Inter-specific**	**Intra-specific**	**Inter-specific**	**Intra-specific**	**Inter-specific**	**Intra-specific**	**Inter-specific**	**Intra-specific**	**Inter-specific**	**Intra-specific**	**Inter-specific**	**Intra-specific**	**Inter-specific**
UHM[1]	-0.68[2]	-0.65	0.36	-0.75	-0.23	0.22	-0.71	-0.42	-0.74	-0.48	-0.74	-0.39	-0.81	-0.44
	<0.01[3]	<0.01	0.08	<0.01	0.28	0.18	<0.01	<0.01	<0.01	<0.01	0.02	0.02	<0.01	<0.01
Str.	0.55	-0.31	0.45	-0.47	0.03	0.06	0.44	-0.17	0.49	-0.18	0.20	-0.37	0.23	-0.35
	<0.01	0.07	0.02	<0.01	0.99	0.72	0.03	0.32	0.02	0.28	0.35	0.03	0.27	0.03
UI	-0.26	-0.14	-0.29	-0.29	0.23	0.41	-0.17	-0.09	-0.26	-0.24	-0.23	-0.46	-0.35	-0.58
	0.22	0.42	0.16	0.09	0.28	<0.01	0.41	0.61	0.22	0.16	0.27	<0.01	0.09	<0.01
Mic.	0.63	0.86	0.12	0.72	-0.17	-0.16	0.52	0.69	0.63	0.70	0.07	0.18	0.14	0.23
	<0.01	<0.01	0.57	<0.01	0.43	0.33	<0.01	<0.01	<0.01	<0.01	0.74	0.28	0.52	0.17
LP			-0.14	0.58	0.30	-0.18	0.95	0.86	0.97	0.87	0.76	0.33	0.80	0.37
			0.52	<0.01	0.15	0.28	<0.01	<0.01	<0.01	<0.01	<0.01	0.05	<0.01	0.02
S/B					-0.37	-0.12	-0.22	0.38	-0.14	0.39	-0.36	0.22	-0.32	0.25
					0.08	0.50	0.31	0.02	0.52	0.02	0.08	0.19	0.13	0.14

[1] See Table 1. [2] Pearson correlation coefficient. [3] Probability of a larger *r* value.

also derive from the statistical model used to estimate genetic parameters.

A good combiner female parent with regard to fiber quality parameters (Askabat-100) was not a good combiner for within-boll yield components. Conversely poor combining males (Sahin-2000) for fiber quality parameters were good combiners for within-boll yield components. Coyle and Smith (1997) indicated that genotypes with positive GCA effects for fiber quality had negative GCA effects for basic within-boll yield components. Thus, they suggested three-way crosses, modified backcross or recurrent selection procedures for improved fiber quality and simultaneous increases in basic within-boll yield components. Generally, good combiners among females and males exhibited better mean performance as reflected by positive associations between them. These positive associations indicate that the parent may be selected on the basis of GCA, mean performance or in combination of the both. The positive GCA effects indicated that continued progress should be positive through breeding for within-boll yield components and fiber quality traits. Similar conclusions were also obtained for F_1 hybrids by Tang *et al.* (1993) and Meredith and Brown (1998).

The SCA effects showed that the best specific combinations were not always obtained from parents with good and positive GCA effects. This finding is inconsistent with previous studies reported by Khan *et al.* (1991), Coyle and Smith (1997), Shakeel *et al.* (2001), Basal and Turgut (2003), and Lukonge *et al.* (2008). The results indicated that a higher GCA does not necessarily confer a higher SCA and that the GCA and SCA were independent of one another a finding similar to the results of Khan *et al.* (2007) and Khan *et al.* (2009). In this study, the hybrid combinations with positive and significant SCA effects produced a high mean value of certain traits (*e.g.*, Aydin-110 × Sahin-2000 for S/B and GW Teks × Carmen for L/S). However, some of the hybrid combinations with positive and significant SCA effects were not able to produce a high mean value of certain traits (*e.g.*, Askabat-100 × Carmen for L/S and TAM 94L-25 × Sahin-2000 for SAS). These results showed that positive and significant SCA effects do not necessarily indicate superior trait performance.

An increase in fiber length (UHM) will cause a decrease in the most basic within-boll yield components, LP, L/S, L/SAS, and F/SAS, in both hybrid populations. Lint percentage is a function of seed weight and lint weight and will increase if either L/S increases or seed weight decreases, as reported by previous studies (Quisenberry, 1975; Basal and Smith, 1997; Smith and Coyle, 1997). Thus, selection for longer fibers in these populations could result in selections having lower lint percentage through lower lint weight per seed, lower lint weight per unit seed surface area, and fewer fibers per unit seed surface area. The positive correlation coefficient between UHM and SAS in an intraspecific F_1 cotton population indicated that as seed size increases, the length of the fiber also increases in the F_1 populations and parents (Table 7). Stewart and Kerr (1974) reported that fibers elongate as long as the seed is increasing in volume. The negative association of UHM with L/S and L/SAS indicates that as length increases, L/S and L/SAS will decrease due to the negative association between UHM and micronaire (data not shown). Since within-boll lint yield is based on the number of spinnable fibers produced within the boll, UHM length was negative and significantly associated with F/S and F/SAS in intraspecific and interspecific F_1 cotton populations. These data suggest that it would not be easy to improve fiber length and within-boll lint yield components simultaneously for these populations. However, increased fiber strength was consistently associated with increased fiber length (data not shown) in interspecific F_1 cotton populations, as reported by Basal and Smith (1997) and Herring *et al.* (2004). These studies indicate that it would be possible to simultaneously select for both fiber strength and length in interspecific (*G. barbadense* × *G. hirsutum*) conventional segregating populations.

Fiber strength was low but negatively associated with all within-boll lint yield components, especially among interspecific crosses. Previous studies also show that fiber strength was negatively correlated with basic within-boll lint yield components (Basal and Smith, 1997; Smith and Coyle, 1997). However, fiber strength was positive and significantly correlated with LP, across the intraspecific F_1 cotton populations. The positive and significant correlation of fiber strength with LP and the low but positive correlation of fiber strength with L/S, L/SAS, F/S, and F/SAS are encouraging for the intraspecific F_1 cotton populations studied. Breeders who could increase fiber strength while increasing lint yield per boll could exploit these positive correlations. These positive associations indicate that as LP, L/S, L/SAS, F/S, and F/SAS increase, fiber strength would also increase. However, the negative and non-significant association between strength and LP, L/S, L/SAS, F/S, and F/SAS for interspecific F_1 cotton populations shows the complex interrelationship of fiber strength with lint yield components. It seems logical that the ultimate way to increase yield per boll is to increase the number of fibers produced, since fibers produced per seed has the greatest effect on lint yield (Bednarz *et al.,* 2007; Rauf *et al.,* 2007). A negative and significant correlation of UI with F/S and F/SAS shows that increasing the number of fibers borne on seeds leads to more variability in the length of fibers (Basal and Smith, 1997).

Micronaire was positively associated with LP, L/S, and L/SAS for both hybridization populations and S/B among the interspecific crosses. These associations were not unexpected because the increase in weight per unit fiber length should be associated with weight relationships within the boll, such as lint percentage, lint weight per seed surface area, and lint weight per seed. The positive association of micronaire with S/B is also reported by Basal and Smith (1997). Among the both hybridization F_1 populations, higher lint percent (LP) was positively associated with higher L/S, L/SAS, F/S, and F/SAS. These results are logical since lint percent is a lint gross production that measures the weight of the lint produced relative to the weight of seed. Harrell and Culp (1976) and Worley *et al.* (1976) suggested that more seed per boll may be desirable because of the greater amount of seed surface area for lint production within the boll. Although limited to these populations, selection for increased numbers of S/B would decrease the seed size, a factor that is desirable according to Harrell and Culp (1976) and Worley *et al.* (1976).

Genotypes having positive GCA effects for fiber quality showed negative GCA effects for basic within-boll yield components. These results indicated that fiber quality and some of the most basic within-boll yield components would be improved simultaneously by using three-way crosses or modified backcross instead of single cross combinations. The positive and significant correlation of fiber strength with LP and the low but positive correlation of fiber strength with L/S, L/SAS, F/S, and F/SAS are encouraging for the studied intraspecific F_1 cotton populations.

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