

IDENTIFICATION OF POTENTIAL PARENTS AND PROMISING CROSSES BASED ON COMBINING EFFECTS FOR IMPROVING PRODUCTIVITY AND FIBER QUALITY IN COTTON

Minka KOLEVA, Valentina DIMITROVA, Neli VALKOVA, Spasimira NEDYALKOVA

Agricultural Academy, Field Crops Institute, Chirpan, Bulgaria

Corresponding author: m_koleva2006@abv.bg

Abstract

The object of this study was 59 F₁ hybrid populations obtained from three schemes of line × tester crosses. The aim was to find the most promising F₁ crosses for improving productivity, lint percentage and fibre length of new cotton varieties. In 2022 and 2023 the crosses and their parents were included in three trials carried out by the block method design in three replicates. The highest values of total GCA effects of the two parents for each trait were taken as “ideal” and the Euclidean distances between them and the GCA effects of both parents were calculated for each F₁ cross. The crosses with the shortest Euclidean distances were considered as the most reliable for the selection. Some crosses were found to exhibit the highest possible GCAs for the three studied traits and appeared to be the most valuable for the breeding programs. There were identified good general combiners for the three traits under study. Some cross combinations showed high and positive SCA effects and heterosis manifestations. Heterobeltiosis was also registered for the three traits most strongly expressed in productivity per plant.

Key words: cotton, line × tester crosses, combining ability, Euclidean distance.

INTRODUCTION

Cotton breeding in Bulgaria is aimed at increasing seed cotton yield and lint yield, by increasing lint percentage and improving fiber quality, especially its length. According to Chapara and Madugula (2021) the creation of a new cultivar having high yield and high fiber quality is of utmost importance for all cotton breeders.

In our country considerable selection work has been carried out to increase yield and improve fiber quality and relatively good results have been achieved (Dimitrova et al., 2022).

Intra- and interspecific hybridization and experimental mutagenesis are the main breeding methods. A number of new varieties and promising lines have been created, which are valuable starting material for further selection work with cotton. According to Ahsan et al. (2015) the quantity and quality of achievable genetic variability provides sufficient opportunities to upgrade and develop breeding activity into a successful breeding program.

In our country, in cotton breeding the latest achievements are the varieties Tsvetelina, Pirin, Perun (Koleva, Valkova, 2019; 2023), Aida,

Anabel, Tiara, Melani (Dimitrova, 2022a, 2022b, 2023) and Selena (Dimitrova & Nedyalkova, 2024). Pirin, Perun and Anabel were obtained from intraspecific crosses, Aida, Tiara, Melani and Selena were created by remote hybridization and backcrossing. These new varieties are very early. Tiara, Melani and Selena have improved fiber quality, while the others have improved productivity combined with other valuable qualities.

Many authors (Mahmood et al., 2020; Ullah et al., 2020, Sarwar et al., 2021) by applying cluster or PC analyses studied genetic diversity to select the superior genotypes for the future breeding programs as well as the genetic distance with the aim of including in one breeding program genetically dissimilar genotypes to increase genetic diversity or genetically similar to achieve greater breeding progress.

Combining ability and potential of parents involved in crosses are essential to the success of breeding programs. Zhang et al. (2016) concluded that the ability to combine yield with fiber quality in F₁ interspecific *G. hirsutum* L. × *G. barbadense* L. crosses depends on the genetic potential and combining ability of parents.

According to Sivia et al. (2017), Nimbal et al. (2019) combining ability analysis plays an important role in selection of parents to obtained more desirable segregants.

The general combining ability (GCA) of genotypes is of greater importance for synthetic selection (for hybridization and selection programs), while the specific combining ability (SCA) is of greater importance for heterosis selection (for hybrid crop exploitation) (Sajjad et al., 2016).

It is known that the general combining ability is closely related to the additive action of genes and that genotypes with high GCA have more additive genes, while high specific combining ability is determined by the non-additive action of genes - dominance and epistasis. For the selection of cotton in our country the GCA is more important with a view to creating synthetic varieties.

Many authors have reported that additive and non-additive gene effects were important for the inheritance of traits in cotton. Some researchers have pointed greater importance of non-additive gene effects, others of additive gene effects.

Non-additive gene action for most of traits was reported by Ali et al (2016a; 2016b), Karademir et al. (2016), Sajjad et al. (2016), Sivia et al. (2017), Ali et al. (2018), Munir et al. (2018). Additive gene effects were predominant in the inheritance of seed cotton yield, boll weight and lint percentage in studies of Vasconcelos et al. (2018) in *G. hirsutum* diallel crosses, for fiber length in studies of Carvalho et al. (2018), Ekinci (2018) in *G. hirsutum* L. $\times$ *G. barbadense* crosses.

Line $\times$ tester crossing analysis gives very useful information about both maternal and paternal forms (Dabholcar, 1992). According to Sivia et al. (2017) this method is one of the simplest and efficient methods of evaluating large number of inbreds for their combining ability.

In practice, in the synthetic selection (hybridization and selection programs) parents having high GCA for one, two or more traits are wanted, such with high GCA for more traits being more desirable. The importance of individual parental forms with high general combining ability for one or more traits is usually emphasized. Barut et al. (2000) applied selection of parents with the highest possible GCA for all studied traits. The GCA effects of

both parents, for each trait and for each combination, were pooled and ranked and the highest value for each trait was taken as “ideal”. The “ideal” values for each trait were considered to characterize the “ideal” population, and the Euclidean distance between the common GCA effects of both parents and the “ideal” population values for each cross was calculated.

In the selection of cotton in our country this approach for selection of parents with the highest possible GCA for all studied traits was applied by Stoilova (2004).

The aim of this study was to identify promising F_1 crosses of greatest selection value for productivity per plant, lint percentage and fibre length, by applying the indicated approach to select parents with as high as possible GCA for the three traits.

MATERIALS AND METHODS

In 2022-2023 the hybrid populations derived from three line $\times$ tester crosses design mating systems, by applying the experimental method I (without reciprocals) of Savchenko (1984) were studied. In the first crossing scheme (5×3) five advanced lines - 639, 662, 678 (Selena variety), 681 and 682 (Bulgarian selection) used as female parents were crossed with one Bulgarian variety - Sirius and two foreign cultivars - Nazili 954 (Turkish) and FR-H-1002 (Spanish) used as male parents to produced 15 hybrid combinations. In the second scheme of crossing (5×4) the same females were crossed with four other males - line 489, Anabel (line 535), Tiara (line 550) and Melani (line 553) varieties (Bulgarian selection) to produced 20 hybrid combinations. In the third crossing scheme (6×4) Kristal, Perun, Pirin, Tiara, Melani and Anabel varieties (Bulgarian selection), used as female parents, were crossed with Aida (Bulgarian variety) and the foreign cultivars Nazili 954 (Turkish), FR-H-1001 (Spanish) and Bridget (Greek), used as male parents, to produced 24 hybrid combinations.

The trials, two in 2022 and one in 2023, were carried out at the Field Crops Institute in Chirpan, in randomized complete block design with three replications. Each plot with parents and hybrids consisted of two rows 2.4 m long with a distance of 0.60 m between rows and 0.20 m within row. Traditional practices for

cotton growing in our country were applied during the growing season. The traits under study were productivity per plant, lint percentage and mean fiber length. For each genotype ten plants from each replication were observed.

Methodology of Savchenko (1984) was applied to evaluate the general combining ability (GCA) and specific combining ability (SCA). The hybrid sum of squares was subdivided into variation due to females, males and the female $\times$ male interaction. The main effects of females and males are equivalent to GCA, and the female $\times$ male interaction represents SCA (Hallauer and Miranda, 1981).

The common GCA effects of both parents for each trait and each combination are presented in Tables 6 and 7. The highest values were taken as “ideal” (Barut et al., 2000) and the Euclidean distances (Manly, 1995) between them and the total GCA effects of both parents for each F_1 cross were calculated. The smaller are the distances to the ideal population, the more desirable are the crosses.

Euclidean distances were determined by the formula:

$$\text{Squared Euclidean distance} = \sum (x_i - x_j)^2$$

where: x_i – the “ideal” value; x_j – the common of both parents. Data were pre-standardized.

In terms of temperature sum in May-September (the growing season of cotton), 2022 was moderately warm ($P = 34.37\%$) and 2023 was warm ($P = 15.5\%$). The temperature sums during the period April-September (cotton growing season) were 113°C and 145°C , respectively for 2022 and 2023, higher than the multi-year average values (data are not given here). In terms of rainfall in May-August both years were average ($P = 46.8\%$ and 51.5%). The shortage of rainfall in the months of July-August (period of flowering and fruiting) was -14.6 mm in 2022 and -39.2 mm in 2023, which combined with higher temperatures $+77^\circ\text{C}$ and $+150^\circ\text{C}$, respectively for the two years, adversely affected the formation and retention of fruit elements and reflected on the seed cotton yield and fiber quality.

$P\%$ is the coverage factor (coefficient of security) for the temperature sum in May-September and for the rainfall in May-August.

RESULTS AND DISCUSSIONS

Results of combining ability variance analysis are given in Table 1.

In 2022, in the first crossing scheme (trial I), for the three studied traits, the effects of crosses, GCA effects of females and SCA effects of crosses were significant. GCA effects of males were significant for productivity per plant and fiber length, and not significant for lint percentage. Therefore, lines used as females differed in GCA for the three traits, while the cultivars used as males differed in GCA for productivity per plant and fiber length, and did not differ in lint percentage. The crosses differed in SCA for the three traits. In the second crossing scheme (trial II), the effect of crosses, GCA of females and SCA of crosses were also significant for the three traits. GCA effects of males were significant for productivity per plant and lint percentage and insignificant for fiber length. Lines used as females differed in GCA for the three traits, while the males differed in GCA for productivity per plant and for lint percentage and did not differ in GCA for fiber length. Crosses differed in SCA for the three traits.

It can be seen from the Table 1 that in 2022 in the two crossing schemes (trial I and trial II), effects of crosses, GCA effects of females and SCA effects of crosses were significant for the three traits. GCA effects of males for productivity per plant were also significant. GCA effects for lint percentage in crosses included in trial I and GCA effects for fiber length in crosses included in trial II were non-significant. Therefore, the lines used as mothers differed in GCA for the three studied traits in both crossing schemes, while the cultivars used as males, in crosses included in trial I differed in GCA for productivity per plant and for fiber length and did not differ for lint percentage.

In trial II, male parents differed in GCA for productivity per plant and lint percentage and did not differ for fiber length. The crosses in the two crossing schemes differed in SCA for the three traits.

In 2023, in the third crossing scheme, effects of crosses were significant at $P \leq 0.001$ for productivity per plant and lint percentage, and significant at $P \leq 0.05$ for fiber length. GCA effects of females and males were significant for

productivity per plant and lint percentage and non-significant for fiber length, meaning that both females and males did not differ in GCA

for this trait. SCA effects of crosses were significant for the three traits.

Table 1. Analysis of combining ability variance for productivity per plant, lint percentage and fiber length in 5×3 , 5×4 and 6×4 line by tester F_1 crosses

Trial	Sources on variation	Degrees of freedom	Productivity per plant	Mean squares Lint percentage	Fiber length
Trial I - 2022	Crosses	14	91,868*** F_{exp} , 61,545	31,413*** F_{exp} , 80,850	3,591** F_{exp} , 14,988
	Errors	28	1,493	0,388	0,239
	GCA-females	4	5,183** F_{exp} , 10,416	33,281** F_{exp} , 256,971	1,370** F_{exp} , 17,150
	GCA - males	2	5,107** F_{exp} , 10,265	0,197ns F_{exp} , 1,523	1,265** F_{exp} , 15,835
	SCA-females $\times$ males	8	49,724** F_{exp} , 99,934	1,633** F_{exp} , 12,613	1,094** F_{exp} , 13,700
	Errors	28	0,497	0,129	0,080
Trial II - 2022	Crosses	19	89,059*** F_{exp} , 47,105	39,406*** F_{exp} , 110,892	2,076*** F_{exp} , 8,116
	Errors	38	1,890	0,333	0,256
	GCA-females	4	11,164** F_{exp} , 17,662	47,174** F_{exp} , 425,235	1,587** F_{exp} , 18,612
	GCA - males	3	27,00** F_{exp} , 42,716	3,471** F_{exp} , 31,285	0,174ns F_{exp} , 2,042
	SCA-females $\times$ males	12	36,531** F_{exp} , 57,796	2,888** F_{exp} , 26,031	0,523** F_{exp} , 6,133
	Errors	38	0,632	0,111	0,085
Trial III - 2023	Crosses	23	256,342*** F_{exp} , 6,133	5,961*** F_{exp} , 10,196	0,442* F_{exp} , 2,339
	Errors	46	1,090	0,584	0,189
	GCA-females	5	124,33** F_{exp} , 227,982	2,041** F_{exp} , 10,475	0,064ns F_{exp} , 1,026
	GCA - males	3	116,799** F_{exp} , 214,171	6,258** F_{exp} , 32,111	0,052ns F_{exp} , 0,825
	SCA-females $\times$ males	15	66,216** F_{exp} , 121,417	1,116** F_{exp} , 5,725	0,193** F_{exp} , 3,063
	Errors	46	0,545	0,195	0,63

* - $p \leq 0.05$; ** - $p \leq 0.01$; *** - $p \leq 0.001$; n.s. - no significant

Estimates of GCA effects for female and male parents are given in Table 2.

In 2022, of the females, line 622 had the highest and significant positive GCA for productivity per plant in both trials (I and II), while line 682 had significant positive GCA in trial I and significant negative GCA in trial II. Of the males, in trial I, the Turkish variety Nazili 954 had positive and significant GCA for productivity per plant.

The Spanish cultivar FR-H-1002 had positive but insignificant GCA. In trial II, from the male parents, Anabel (line 535) and Melani (line 553) varieties had high and significant GCA for productivity per plant. Melani variety (line 553) had the highest productivity among males. Line 681 of females in both trials and Sirius variety

of males in trial I having the highest productivity per plant exhibited significant negative GCA.

In crosses tested in 2023, from the females, the highest positive GCA for productivity per plant was found for Kristal variety, followed by Tiara (line 550) variety. Pirin variety showed the highest productivity per plant had negative GCA for this trait. Of the males, the Spanish cultivar FR-H-1001 had the highest GCA, followed by the Turkish cultivar Nazili 954. Anabel (line 535), Tiara (line 550) and Melani (line 553) varieties used as males in the crosses tested in 2022 in trial II, and used as females in the crosses tested in 2023, demonstrated different combining ability. Probably the year conditions were also essential for the combining ability manifestation of genotypes.

Table 2. Evaluation of GCA effects for productivity per plant, lint percentage and fiber length in 5×3 , 5×4 and 6×4 line by tester F_1 crosses

Trials		Parents	Productivity per plant		Lint percentage		Fiber length	
			g	GCA	%	GCA	mm	GCA
Trial I 2022	Females	639	43.3	0.203	40.9	1.465	24.5	0.135
		662	44.0	1.525	42.1	3.627	25.4	-0.875
		678	48.0	-1.280	40.3	1.988	26.5	-0.509
		681	52.2	-1.408	35.7	-3.712	26.0	0.591
		682	40.4	0.959	34.7	-3.368	26.9	0.658
		Standard error		0.705		0.360		0.283
	Males	Sirius	56.7	-1.110	39.3	0.135	25.2	-0.313
		Nazili 954	45.8	0.867	41.8	-0.228	25.6	-0.267
		FR-H-1002	34.0	0.243	40.4	0.092	26.9	0.580
Standard error			0.546		0.279		0.219	
Trial II 2022	Females	639	47.3	-0.878	41.6	2.210	25.5	-0.211
		662	48.6	2.947	41.9	2.294	24.7	-0.111
		678	52.6	-0.528	42.0	2.960	25.6	-0.836
		681	52.4	-0.420	37.6	-4.181	27.3	0.297
		682	47.8	-1.120	35.8	-3.283	26.8	0.962
		Standard error		0.687		0.288		0.253
	Males	489	47.7	-1.713	41.9	0.724	25.8	0.020
		Anabel (535)	41.4	2.133	39.2	-0.339	25.1	0.194
		Tiara (550)	46.5	-2.287	41.2	0.635	25.3	-0.255
		Melani (553)	50.0	1.866	40.3	-1.019	25.5	0.040
		Standard error		0.615		0.256		0.226
Trial III 2023	Females	Kristal	29.1	10.807	38.6	-0.042	25.7	-0.215
		Perun	33.9	-2.189	38.2	0.708	25.1	0.031
		Pirin	47.8	-2.743	38.8	0.421	24.8	-0.006
		Tiara (550)	37.8	1.111	40.2	0.412	25.2	0.056
		Melani (553)	34.0	-2.914	39.5	-0.212	25.7	-0.039
		Anabel (535)	27.8	-4.072	38.9	-1.287	25.9	0.173
		Standard error		0.639		0.381		0.216
		Males	Aida	27.6	-2.761	41.8	-0.569	25.9
	Nazili 954		25.8	1.105	40.3	-0.778	25.9	0.130
	FR-H-1001		32.8	5.736	39.6	-0.131	26.4	-0.003
	Bridget		22.6	-4.081	43.2	1.478	26.5	-0.090
	Standard error			0.522		0.312		0.177

The foreign cultivars, the Turkish Nazili 954 and the Spanish FR-H-1001 demonstrated very good GCA with the Bulgarian varieties. Both cultivars are highly productive, but under our conditions, in some years they are late in maturing and seed cotton yields are uncertain. SCA effects of crosses for the three traits are presented in Tables 3-5. In 2022, in trial I, 7 crosses exhibited positive and significant SCA effects for productivity per plant. The crosses 681× Nazili 954, 662 × Nazili 954, and 682 × FR-H-1002 were found to have high SCA effects and highest productivity per plant from 52.4 g to 56.9 g. The specified cross combinations manifested mid parent heterosis from 116.1% to 140.9% and heterobeltiosis from 109.0% to 129.7%. Lines 662 and 682 from the females, showed high GCA for this trait, had low SCA variances, while the cultivar

Nazili 954 from the males, showed high GCA, had high SCA variances, which should be taken into account in the selection strategy.

In trial II, 10 crosses showed positive and significant SCA effects. In these crosses the productivity per plant varied from 40.0 g to 59.2 g and mid parent heterosis ranged from 102.1% to 131.2%. Heterobeltiosis was registered in 6 crosses from 101.3% to 122.4%. Crosses 662 × Tiara and 682 × Anabel showed the highest productivity per plant (59.2 g and 58.5 g) and manifested the highest heterobeltiosis (121.8% and 122.4%). Line 662 from the females with high GCA demonstrated high SCA variances, while Anabel and Melani varieties from the males also with high GCA had respectively high and low SCA variances.

In 2023, the productivity per plant was lower compared to 2022, except for the cross

combination Kristal $\times$ FR-H-1001. Seven crosses were found to have positive and significant SCA effects for productivity per plant. In these crosses mid parent heterosis was 109.5-227.0%. Only three crosses manifested heterobeltiosis from 112.9% to 214.0%. Tiara variety (line 550) from the females and the cultivar Nazili 954 from the males, with high GCA effects, had low variances of SCA and are very suitable for synthetic (pedigree) selection. Kristal variety from the females and the cultivar FR-H-1001 from the males with high GCA had high SCA variances and are more suitable for heterosis selection.

Patel et al. (2014) in interspecific *G. hirsutum* $\times$ *G. barbadense* hybridization reported heterobeltiosis (better parent heterosis) up to 35.49% for seed cotton yield. In this hybridization positive mid parent heterosis for this trait was reported by Adzare et al. (2017), Rajeev et al. (2018).

In 2022, 5 crosses in trial I and 7 crosses in trial II demonstrated positive and significant SCA effects for lint percentage. In these crosses, lint percentage ranged from 39.2% to 41.9%. Mid parent heterosis from 102.0 to 106.4% was registered in 9 crosses and heterobeltiosis from 101.4 to 105.9% was found in 6 crosses. Lines 639 and 678 from females in trial I and trial II, and line 489 and Tiara variety (line 550) from males in trial II, with high GCA, had low SCA variances. Line 662 from the females having high GCA demonstrated non-constant SCA variances, high in trial I and low in trial II.

In 2023, only three crosses demonstrated high and significant SCA effects for lint percentage. In these crosses, mid parent heterosis was 102.0-108.7%, while heterobeltiosis 101.1-107.6% was registered in only two crosses. Pirin and Perun varieties from the females, and the cultivar Bridget from the males, with high GCA, had low SCA variances and can be used in synthetic (pedigree) selection. Tiara variety (line 550) displayed high SCA variances. This variety and the Turkish cultivar Nazili 954 demonstrated non-constant SCA variances.

Line 622 with high GCA for productivity/plant and lint percentage showed inconsistent SCA variances for both traits. Tiara variety, used as female parent (in 2023) and male parent (in trial II, 2022), having high GCA in both years, also had inconsistent SCA variances for both traits.

The results for mid parent heterosis for this trait 102.0-108.7% (in 12 crosses) and heterobeltiosis 101.1-107.6% (in 8 crosses) are comparable to those reported by other authors. Karademir & Gençer (2010) reported heterosis of 5.52% in only one cross among studied diallel crosses.

Regarding fiber length, in 2022, 5 crosses in trial I and 3 crosses in trial II showed high SCA effects. In these crosses, fiber length varied from 26.0 mm to 28.3 mm. In all crosses, except one, mid parent heterosis was accounted for from 102.0% to 108.3% and heterobeltiosis was registered from 101.5% to 107.3%. The longest fibers 28.3 mm and 28.1 mm and pronounced heterobeltiosis of 105.2% and 107.3% were found in the crosses 681 $\times$ FR-H-1002 (trial I) and 682 $\times$ Anabel (line 535) (trial II). Line 681 of females, showed high GCA had low SCA variances in both trials, while line 682, also with high GCA for this trait, demonstrated inconsistent low and high SCA variances, respectively.

In 2023, only three crosses displayed significant positive SCA effects for fiber length and manifested mid parent heterosis of 103.1-108.3% and heterobeltiosis of 101.9-105.8%.

Positive heterosis for fiber length was reported by Bölek et al. (2014), Roy et al. (2018) in *G. hirsutum* $\times$ *G. barbadense* hybridization. In this hybridization Çoban et al. (2015) reported that heterosis values for this trait were positive and ranged between 2.05% to 16.9%. Çoban and Ünay (2017) reported mid parent heterosis for fiber length in all cross combinations. Ünay et al. (2018) among the studied *G. hirsutum* $\times$ *G. barbadense* crosses found that heterosis (Ht) values for fiber length varied from -1.77 to 3.81%, the heterobeltiosis (Hb) values varied from -7.87% to -0.03%. Chapara & Madugula (2021) reported heterosis for Upper Half Mean Length (UHML) and mean length in intraspecific line $\times$ tester crosses and the highest values were 21.34% and 25.37%, heterobeltiosis for UHML ranged between 7.53 to 20.73%. In our study heterosis values for mean fiber length were in agreement with those reported in the literature or lower, mid parent heterosis varied from 102.0% to 108.3%, heterobeltiosis varied from 101.5% to 107.3%.

According to Ekinçi & Basbag (2018) estimation of heterotic effects is necessary to

identify new promising cross combinations. In addition, transgressive segregation in F₂ and occurrence of transgressive variability can be expected in pedigree selection. The heterosis results reported in this study for the three traits are comparable to those reported by other

authors or lower (for fiber length), which is understandable given that in interspecific crosses of the tetraploid species *G. hirsutum* and *G. barbadense* the dominance and heterosis manifestations are more strongly expressed than those in intraspecific crosses.

Table 3. Mean values, effects of specific combining ability (below line) and variances (σ^2S_i ; σ^2S_j)
Trial I - 2022

Traits	Females	Males			σ^2S_i
		Sirius	Nazili 954	FR-H-1002	
Productivity per plant, g		51.3	49.8	43.7	
	639	4.127	0.667	-4.793	20.181
		50.5	53.3	45.0	
	662	1.971	2.878	-4.849	17.795
		46.5	39.0	54.8	
	678	0.877	-8.650	7.773	67.964
		37.4	56.9	45.7	
	681	-8.145	9.394	-1.249	78.038
		49.1	45.6	52.4	
	682	1.171	-4.289	3.118	14.699
	σ^2S_j	22.307	47.505	29.504	
	SE (SCA)			0.834	
Lint percentage, %		40.9	39.0	40.8	
	639	0.531	-0.972	0.441	0.699
		41.1	44.6	41.5	
	662	-1.447	2.433	-0.987	4.482
		40.6	40.0	41.7	
	678	-0.291	-0.528	0.819	0.505
		36.1	34.4	34.7	
	681	0.909	-0.428	-0.481	0.609
		35.8	34.7	35.7	
	682	0.298	-0.505	0.208	0.182
	σ^2S_j	0.832	1.885	0.516	
	SE (SCA)			0.426	
Fiber length, mm		25.2	26.3	27.3	
	639	-0.742	0.278	0.464	0.415
		24.2	26.0	25.5	
	662	-0.698	0.989	-0.291	0.768
		26.9	24.6	25.3	
	678	1.602	-0.711	-0.891	1.926
		25.6	26.2	28.3	
	681	-0.831	-0.211	1.042	0.904
		27.1	26.2	27.0	
	682	0.669	-0.344	-0.324	0.329
	σ^2S_j	1.179	0.424	0.564	
	SE (SCA)			0.333	

Table 4. Mean values, effects of specific combining ability (below line) and variances (σ^2S_i ; σ^2S_j)
Trial II - 2022

Traits	Females	Males				σ^2S_i
		489	Anabel (535)	Tiara (550)	Melani (553)	
Productivity per plant, g	639	47.5	50.0	41.6	56.8	20.830
		0.238	1.108	-5.088	5.958	
	662	55.1	47.7	59.2	49.2	57.861
		4.013	-7.233	8.687	-5.467	
	678	50.0	54.2	39.8	53.3	23.290
		2.288	2.742	-7.238	2.108	
	681	38.1	49.5	49.1	52.0	1.897
		0.380	-2.067	0.987	0.700	
Lint percentage, %	639	40.0	58.5	49.1	47.3	41.933
		7.019	7.667	2.653	-3.300	
	σ^2S_j	17.760	30.966	40.376	20.240	
	SE (SCA)			1.020		
	639	43.0	42.4	43.2	38.7	1.975
		0.459	0.889	0.748	-2.097	
	662	42.0	40.6	43.0	42.1	0.955
		-0.657	-0.960	0.464	1.153	
Fiber length, mm	678	43.7	40.1	44.0	42.6	2.148
		0.343	-2.160	0.764	1.052	
	681	38.0	34.4	34.7	34.7	1.959
		1.851	-0.752	-1.360	0.261	
	682	35.3	39.0	36.5	35.0	4.457
		-1.997	2.983	-0.637	-0.370	
	σ^2S_j	2.032	3.950	0.887	1.749	
	SE (SCA)			0.429		
Fiber length, mm	639	26.3	25.6	25.7	26.0	0.176
		0.305	-0.602	0.313	-0.015	
	662	25.5	26.2	26.1	26.9	0.371
		-0.066	-0.302	0.213	0.751	
	678	26.6	25.7	24.2	25.0	0.777
		1.162	0.156	-0.895	-0.424	
	681	26.8	26.6	26.4	26.2	0.066
		0.296	-0.110	0.138	-0.324	
Fiber length, mm	682	26.0	28.1	27.1	27.1	0.659
		1.102	0.858	0.232	0.012	
	σ^2S_j	0.788	0.298	0.246	0.204	
	SE (SCA)			0.375		

Table 5. Mean values, effects of specific combining ability (below line) and variances (σ^2S_i ; σ^2S_j)
Trial 2023

Traits	Females	Males				σ^2S_i
		Aida	Nazili 854	FR-H-1001	Bridjet	
Productivity per plant, g	Kristal	27.4	46.3	70.2	40.3	198.16
		-15.91	-0.885	18.385	-1.582	
	Perun	34.2	30.8	34.0	33.3	22.777
		3.878	-3.389	-4.819	4.331	
	Pirin	30.0	40.3	38.3	21.6	30.633
		0.232	6.665	0.001	-6.899	
	Tiara	36.5	42.9	33.9	32.3	34.920
		2.844	5.411	-8.219	-0.036	
	Melani	37.7	29.5	34.1	28.2	32.520
		8.103	-3.997	-4.011	-0.094	
	Anabel	29.3	28.5	35.6	31.4	11.721
		0.861	-3.805	-1.336	4.281	
	σ^2S_j	68.54	23.23	89.275	17.379	
	SE (SCA)			0.977		
Lint percentage, %	Kristal	27.4	46.3	70.2	40.3	198.16
		-15.91	-0.885	18.385	-1.582	
	Perun	34.2	30.8	34.0	33.3	22.777
		3.878	-3.389	-4.819	4.331	
	Pirin	30.0	40.3	38.3	21.6	30.633
		0.232	6.665	0.001	-6.899	
	Tiara	36.5	42.9	33.9	32.3	34.920
		2.844	5.411	-8.219	-0.036	
	Melani	37.7	29.5	34.1	28.2	32.520
		8.103	-3.997	-4.011	-0.094	
	Anabel	29.3	28.5	35.6	31.4	11.721
		0.861	-3.805	-1.336	4.281	
	σ^2S_j	68.54	23.23	89.275	17.379	
	SE (SCA)			0.584		
Fiber length, mm	Kristal	25.6	26.9	26.3	26.3	0.199
		-0.638	0.428	0.062	0.148	
	Perun	26.7	27.0	26.1	26.4	0.101
		0.199	0.299	-0.434	-0.065	
	Pirin	27.4	26.0	26.4	26.3	0.428
		0.903	-0.680	-0.130	-0.094	
	Tiara	26.4	26.7	26.4	26.7	0.020
		-0.109	0.008	-0.126	0.227	
	Melani	26.5	26.3	26.9	26.2	0.099
		0.037	-0.313	0.437	-0.160	
	Anabel	26.3	27.1	26.9	26.5	0.080
		-0.392	0.258	0.191	-0.056	
	σ^2S_j	0.279	0.173	0.084	0.016	
	SE (SCA)			0.332		

Tian et al. (2019) concluded that overdominance is the genetic basis of lint yield heterosis in interspecific hybrids between *G. hirsutum* L. $\times$ *G. barbadense* L., which is confirmed in studies with intraspecific hybrids. Borzan & Güvercin (2021) support that F₁ hybrids can be more superior from mean of parents (mid parent heterosis) and superior parent (heterobeltiosis)

because of the influence of dominant genes. The GCA and SCA of parents, the heterosis manifestations, as well as the SCA variances should be taken into account when choosing the selection strategy and conducting the selection practices.

The common GCA effects (f_i+m_j) of parents for each trait and ranked crosses based on the

Euclidean distances to the “ideal” population are presented in Tables 6 and 7. According to the calculated Euclidean distances the closest to the “ideal” population and the most valuable for cotton breeding programs in trial I were the crosses 639 × FR-H-1002, 662 × FR-H-1002, 639 × Nazili 954 and 682 × FR-H-1002. Of the females, line 639 had high GCA for lint percentage, line 662 had high GCA for productivity per plant and lint percentage, and line 682 had high GCA for productivity per plant and fiber length. Of the males, the cultivar Nazili 954 had high GCA for productivity per plant and the cultivar FR-H-1002 had high GCA for fiber length. These parental components had low

SCA variances for the respective traits, except for the cultivar Nazili 954 for productivity per plant and line 662 for lint percentage. The low variances of SCA indicate that their high GCA was mainly due to additive gene action and desirable segregants for the respective traits can be expected in the earlier hybrid generations. For the cultivar Nazili 954 and line 662, the high SCA variances show that their high GCA, respectively for productivity per plant and lint percentage, was due to additive and non-additive gene action (dominance and epistasis) and the selection for these traits will be more effective in later hybrid generations.

Table 6: Common combining effects of parents for each trait and square Euclidean distance to ideal values, Trial I – 2022

Parents	Productivity per plant, g	Lint percentage	Fiber length, mm	Square Euclidean distance
Trial I - 2022				
639 × FR-H-1002	0.446	1.558	0.715	2.701
662 × FR-H-1002	1.768	3.720	-0.295	4.285
639 × Nazili 954	1.069	1.237	-0.132	4.742
682 × FR-H-1002	1.202	-3.275	1.237	5.833
682 × Nazili 954	1.825	-3.596	0.390	7.078
678 × FR-H-1002	-1.037	2.081	0.072	7.996
639 × Sirius	-0.906	1.6	-0.178	8.92
682 × Sirius	-0.15	-3.233	0.344	9.452
662 × Nazili 954	2.392	3.399	-1.142	9.922
678 × Nazili 954	-0.414	1.76	-0.775	11.072
681 × FR-H-1002	-1.165	-3.619	1.171	11.448
681 × Nazili 954	-0.542	-3.94	0.324	11.577
662 × Sirius	0.417	3.762	-1.188	12.061
678 × Sirius	-2.389	2.123	-0.821	18.045
681 × Sirius	-2.517	-3.577	0.278	18.168
Trial II - 2022				
662 × Anabel	5.08	1.955	0.083	2.903
662 × Melani	4.813	1.274	-0.071	4.077
639 × Anabel	1.255	1.871	-0.017	5.710
662 × 489	1.234	3.018	-0.091	5.917
639 × Melani	0.988	1.19	-0.171	7.289
682 × Anabel	1.013	-3.622	1.056	7.596
662 × Tiara	0.66	2.929	-0.366	8.600
682 × Melani	0.746	-4.303	0.902	8.994
681 × Anabel	1.713	-4.52	0.491	9.021
678 × Anabel	1.605	2.621	-0.642	9.906
681 × Melani	1.446	-5.201	0.337	10.961
678 × Melani	1.338	1.94	-0.796	11.892
639 × 489	-2.591	2.934	-0.191	13.252
682 × 489	-2.833	-2.559	0.882	13.272
681 × 489	-2.133	-3.457	0.317	14.245
682 × Tiara	-3.407	-2.648	0.607	15.276
639 × Tiara	-3.165	2.845	-0.466	16.753
681 × Tiara	-2.707	-3.546	0.042	17.002
678 × 489	-2.241	3.684	-0.816	17.795
678 × Tiara	-2.815	3.595	-1.091	22.173

Table 7. Common combining effects of parents for each trait and square Euclidean distance to ideal values - Trial 2023

Parents	Productivity per plant, g	Lint percentage	Fiber length, mm	Square Euclidean distance
Trial 2023				
Tiara × FR-H-1001	6.85	0.28	0.053	6.847
Perun × FR-H-1001	3.55	0.58	0.028	7.908
Tiara × Nazili 954	2.21	-0.37	0.186	8.772
Perun × Nazili 954	-1.09	-0.07	0.161	9.934
Pirin × FR-H-1001	3.00	0.29	-0.009	10.004
Tiara × Bridget	-2.97	1.89	-0.034	11.759
Pirin × Nazili 954	-1.64	-0.36	0.124	11.983
Melani × FR-H-1001	2.83	-0.34	-0.042	13.323
Tiara × Aida	-1.65	-0.16	0.019	13.518
Kristal × Nazili 954	11.9	-0.82	-0.085	14.348
Anabel × FR-H-1001	1.67	-1.42	0.170	14.377
Perun × Bridget	-6.27	2.19	-0.059	15.324
Melani × Nazili 954	-1.81	-0.99	0.091	15.571
Perun × Aida	-4.95	0.14	-0.006	15.779
Anabel × Bridget	-8.15	0.19	0.083	16.404
Pirin × Bridget	-6.82	1.9	-0.096	17.243
Kristal × FR-H-1001	16.54	-0.17	-0.218	17.505
Pirin × Aida	-5.5	-0.15	-0.043	18.417
Kristal × Bridget	6.72	1.44	-0.305	18.999
Melani × Bridget	-6.99	1.27	-0.129	19.308
Anabel × Nazili 954	-2.97	-2.07	0.303	20.663
Kristal × Aida	8.04	-0.61	-0.252	21.462
Melani × Aida	-5.67	-0.78	-0.076	22.349
Anabel × Aida	-6.83	-1.86	0.136	23.940

Three more crosses 682 × Nazili 954, 678 × FR-H-1002 and 639 × Sirius with relatively short Euclidean distances to the “ideal” population were also valuable for selection programs. Line 678 from the females had high GCA for lint percentage and low SCA variances.

In trial II, the most reliable were the crosses 662 × Anabel, 662 × Tiara, 639 × Anabel and 662 × 489. In the first two crosses, both parents had high GCA for productivity per plant and line 662 had also high GCA for lint percentage. In the other two crosses, one parent (662 and Anabel) had high GCA for productivity per plant, while the other parent (639 and 489) had high GCA for lint percentage. Lines 662 and Anabel showed high GCA for productivity per plant had high SCA variances, which means, that selection for productivity should be conducted in later hybrid generations. Lines 662 and 639 with high GCA for lint percentage had low SCA variances, which means, their high GCA was due to additive gene action and selection for this trait can carried out in the earlier hybrid generations. High efficiency of selection for this trait in early segregating generations can be expected in the cross combination 662 × 489, where both

parents had high GCA and low SCA variances for lint percentage.

In the trial conducted in 2023, the most valuable cross combinations were Tiara × FR-H-1001, Perun × FR-H-1001, Tiara × Nazili 954 and Perun × Nazili 954. Tiara variety and the cultivars FR-H-1001 and Nazili 954 had high GCA for productivity per plant. Tiara variety and Nazili 954 had low SCA variances, while FR-H-1001 had high SCA variances. Consequence, in the crosses Tiara × Nazili 954 and Perun × Nazili 954 selection for productivity per plant can be effective in earlier segregating generations. In the cross Tiara × Nazili 954 both parents had high GCA and low SCA variances and the election by this trait in early segregating generations will be more effective. Perun variety had high GCA and low SCA variances for lint percentage. In the crosses Perun × FR-H-1001 and Perun × Nazili 954 selection for this trait can also be effective in earlier segregating generations.

Barut et al. (2000) concluded that evaluating parents in multiple environments and ranking crosses by the Euclidean distance to the “ideal”

population can be a simple and effective method of selecting desirable crosses.

In the trial I, the cross 681 × Nazili 954 had the highest productivity per plant, the cross 662 × Nazili 954 had the highest lint percentage, and the cross 681 × FR-H-1002 had the longest fiber, all these crosses showed positive SCA effects and heterosis to the better parent (heterobeltiosis) for the respective traits (109.0 %, 105.9 % and 105.2 %, respectively). In the first two crosses, only one of the two parents exhibited high GCA for the respective traits, while in the third cross both parents had high GCA effects and low variances for fibre length, which means the selection can be made in early segregating generations. These crosses were at an average distance from the “ideal” population. Sivia et al. (2017), Vasconcelos (2018) in line × tester and in diallel cotton crosses (*Gossypium hirsutum* L.) also reported crosses exhibited significant SCA have involved at least one parent with high or average GCA for a particular trait.

In the trial II, the cross 662 × Tiara showed the highest productivity, the cross 678 × 550 had the highest lint percentage and the cross 682 × 535 was with the longest fiber, all crosses exhibited high SCA and heterobeltiosis of 121.0 %, 104.8 and 107.3 %, respectively. In the first and third crosses, only one of the two parents expressed high GCA and high SCA variances for the respective traits, while in the second cross, both parents had high GCA and low SCA variances for lint percentage. These crosses were also at an average distance from the “ideal” population.

In 2023 (trial III), the cross Kristal × FR-H-1001 showed the highest productivity per plant, the cross Perun × Bridget had the highest lint percentage, and the cross Pirin × Aida formed the longest fiber, all demonstrated high SCA for the respective traits. In the first cross, both parents had high GCA and high SCA variances, in the second cross, both parents had high GCA and low SCA variances and appeared to be very valuable for pedigree selection. These crosses were relatively more distant from the “ideal” population.

The crosses 662 × Nazili 954, 662 × Melani and Kristal × FR-H-1001, respectively in trial I, trial II and trial III, had the highest GCA for the productivity per plant. The first two crosses exhibited positive GCA for lint percentage and

negative one for fiber length. In these two crosses, the increase in productivity can lead to strong reduction in fiber length. The third cross had negative GCA for lint percentage and fiber length, and increasing productivity can result in reduction of both traits.

The crosses 662 × FR-H-1002, 662 × Nazili 954, 662 × Sirius (trial I), 662 × 489, 662 × Tiara, 639 × 489, 678 × 489, 678 × Tiara (trial II), Tiara × Bridget and Perun × Bridget (trial III) had the highest GCA for lint percentage. All these crosses showed negative GCA for fiber length, some also for productivity per plant. Therefore, in these crosses increasing the yield can lead to strong shortening of fiber length and in crosses with negative GCA for productivity per plant can lead to decrease in productivity.

Crosses 682 × FR-H-1002, 681 × FR-H-1002 (trial I), 682 × Anabel, 682 × Melani and 682 × 489 (trial II) having high GCA for fiber length, had negative GCA effects for lint percentage. In these crosses, with fiber length increase decrease in lint percentage and in some cases also in productivity, in crosses with negative GCA for this characteristic, can be expected.

Analysis of the research results gives very useful information about the selection of parental components on the basis of their general or specific combining abilities, as well as to select the desired F₁ crosses depending on the selection objectives for improvement of one or more characters. The selection of parental forms based on the common GCA effects of the two parents for all studied traits and selection of F₁ crosses based on the shortest Euclidean distances to the “ideal” population can help to better optimize the existing negative correlations between the traits in cotton.

CONCLUSIONS

Crosses with relatively short Euclidean distances to the “ideal” population in which desirable segregants are expected to occur were selected.

The crosses 639 × FR-H-1002, 662 × FR-H-1002, 639 × Nazili 954, 682 × FR-H-1002, 662 × Anabel, 662 × Melani, Tiara × FR-H-1001 and Perun × FR-H-1001 exhibited as high as possible general combining ability for the three studied traits and appeared to be most valuable for the breeding programs.

The approach to select the parental components having the highest possible general combining ability for all studied traits gives very useful information about their breeding value and helps to select most promising F₁ crosses, in which substantial improvement in one or more characters is expected as well as optimizing the existing negative correlations in cotton.

Some crosses showed high positive specific combining ability effects and heterosis manifestations for one or two traits. Heterobeltiosis values for productivity per plant ranged from 101.3 % to 214.0 %, for lint percentage - from 101.1 % to 107.6 % and for fiber length - from 101.5 % to 107.5 %.

Lines 662, 682, Kristal and Tiara varieties from the females, the cultivars Nazili 954, FR-H-1001 and Anabel and Melani varieties from the males, were identified as very good general combiners for productivity per plant. Line 682, Melani and Tiara varieties had low SCA variances and appear to be very valuable for the recombinant breeding programs, while the others (Nazili 954 and line 662) had high or unstable SCA variances and are more suitable for the heterosis selection.

Lines 639, 662, 678 and Perun, Pirin and Tiara varieties from females, and lines 489 and the cultivar Bredget from males were identified as very good general combiners for lint percentage. Lines 639, 678, 489, Tiara variety and the cultivar Bridget had low SCA variances and are very suitable for the synthetic selection in creating of new cotton varieties. The Greek cultivar Bridget having the highest lint percentage appears to be especially valuable for the selection of this trait.

Lines 681 and 682 from the females and the cultivar FR-H-1002 from the males were very good combiners for fiber length all with low SCA variances.

Reliable F₁ cross combinations, having high general combining ability for the three studied traits or for individual traits as productivity per plant, lint percentage and fibre length, were selected.

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