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RESEARCH ARTICLE

Heterosis and combining ability for phenological yield and fiber traits of cotton (*Gossypium hirsutum* L.) genotypes

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Abstract

The seeds of 4 lines, 3 testers, and their 12 F1 hybrids were sown in a randomized complete block design (RCBD) with 3 replications at Botanical Garden, Department of Plant Breeding and Genetics, Sindh Agriculture University, Tandojam during Kharif 2019. F1 hybrids were raised for the estimation of heterotic effects, GCA and SCA for days to 1st squaring, days to 1st boll formation Bolls opened at 90 days after sowing, Sympodial branches plant^{-1}, Bolls plant^{-1}, Boll weight (g), Seed cotton yield plant^{-1} (g), 100-seed weight (g), Ginning outturn (%) and staple length (mm). Genotypes, parents, crosses, parent's v/s crosses, lines, testers and line × testers were significant for days to 1st squaring and days to 1st boll forming. Bolls unveiled their fissures precisely 90 days post-sowing, while parameters including sympodial branches per plant, bolls per plant, individual boll weight, seed cotton yield per plant, 100-seed weight, ginning outturn, and staple length underwent meticulous evaluation. The statistical scrutiny unveiled the insignificance of both lines and testers concerning the 90-day boll dehiscence. Similarly, the parental influence on boll weight, 100 -seed weight, and staple length exhibited a lack of statistical significance. Line CRIS-134, Sindh, and tester FH-901 gave a higher mean performance for all the traits. Among the hybrids, Mehran × FH-901, Sindh-1 × CIM-602, CRIS-134 × CIM-602, CRIS-342 × Koonj, and CRIS-342 × CIM-602 gave a desirable mean performance and heterotic effect for all the traits. CRIS-342 × Koonj produced maximum SCA effects for bolls per plant. Mehran × FH-901 recorded higher SCA effects for seed cotton yield plant^{-1} and 100-seed weight, CRIS-342 × CIM-602 for lint percentage, and CRIS-342 × FH-901 for staple length. It is suggested that these lines and testers should be utilized in the breeding program to improve these traits.

Keywords

crosses; combining ability; cotton; fiber traits; genotypes; heterosis

Introduction

One of the significant fiber crops is our country's cotton (*Gossypium hirsutum* L.). Being a cash crop, it has a vital role in the country's economy for earning foreign exchange. Many countries worldwide grow cotton as a significant crop, such as the USA, China, India, Pakistan, Uzbekistan, Australia and Africa (1). According to the Economic Survey of Pakistan (2), cotton is measured as the lifeline of the country's economy because the cotton contribution is 0.8% share of GDP; it also gave 4.5% in agriculture value addition. Cotton production remained moderate at 9.861 million bales, a decrease of 17.5% over last year's production of 11.946 million bales and 31.5% against the target of 14.4 million bales. This below-expectation performance of the crop was primarily due to contraction in the cultivated area on account of less economic incentive to the farmers by 12.1% to 2373 thousand hectares compared to last year's area of 2700 thousand ha (Economic Survey of Pakistan, Cotton breeder selected genotypes for development through different breeding methods and breeding techniques. It requires a long growing season, plenty of sunshine and water during its growth, and dry weather for harvest. Cotton crops share 1.0% of GDP and donate 5.5% of cost accumulation to Agriculture. It is the 6th largest basis of vegetable oil. It can increase any country's economy by making edible oil for human consumption, animal feed, and local textile industry consumption. Several people profit from cotton in clothing manufacturing, textile industries, edible industries, and dairy products (3).

There are 4 commercially cultivated species of cotton. Still, the most essential commercial common cultivated species of cotton is (*Gossypium hirsutum* L.) a tetraploid species that has chromosome No: 2n = 52, now known as upland cotton, which provides 90% fiber production, whereas (*Gossypium barbadense* L.) known as Egyptian cotton offers only 3% fiber production. Hence, these species are known as New World cotton. While the other 2 species (*Gossypium arboreum* L.), known as "tree cotton" and (*Gossypium herbaceous* L.) which is mainly grown in East Africa and Southeast East Asia (4).

However, the adverse connotation between Yield and fiber strength and efforts to increase fiber quality through conventional breeding methods are significant problems a cotton breeder faces. For developing potential hybrids in cotton, it is essential to achieve economic heterosis through the genetic variance of the good combining ability of parents, which can lead to higher production and productivity (5).

Gene action is the essential criterion for selection in cotton crops. However, heterosis and combining ability are crucial statistical approaches for improving cotton yield and fiber quality traits (6). Heterosis studies the achievement crosses with high genetic potential while associated with their better parents for different characteristics. In comparison, heterosis is beneficial when a new combination performs better than its parents (7). However, heterosis breeding improves cotton's economic Yield and fiber characteristics (8). Heterosis breeding also improved Yield contributing traits with desired fiber quality in cotton (9). Sprague and Tatum (1942) used GCA and SCA to estimate the average show of line, tester, and hybrid combination (10).

It was reported that significant mean squares owing to both male and female parents determine the general combining ability (GCA) designated as the main effect of additive variances promoting the studied parameters (11). They reported that dominant gene action signifies the possibility of hybrid crop development. It was also described that the hybrid GJHV-337 × GN recorded the highest heterotic effect (1). Cot-22, GJHV-337 × EC-10786 and GN.Cot-22 × KH-119 proved that 125 hybrids are promising hybrids in their study over the standard check for cotton seed yield plant^{-1} and yield attributing traits. Those hybrids showed maximum heterosis for seed cotton yields plant^{-1} also had maximum heterosis for yield-attributing qualities. The existing information in cotton exhibited the values of both additive and non-additive and the main importance of SCA. It indicates a higher chance of producing F_1 hybrids for bolls plant^{-1}, boll weight, seed cotton yield, and lint yield (12). Cotton is the main product in the textile sector, which produces most products related to human aspects (13). Cotton geriatrics play an essential role in the human environmental condition, also related to humans' physical and chemical aspects (14, 15).

Considering the need for a higher yield of cotton to face the ever-increasing human population, The primary objective of this study is to elucidate valuable insights into the heterosis of parental traits and the combining ability within diverse plant characteristics of cotton. This comprehensive investigation aims to provide essential guidance for cotton breeders, facilitating the strategic development of hybrid cotton varieties and the creation of segregated populations. The goal is to empower breeders in the meticulous selection of transgressive segregates, ensuring the enhancement and sustainable improvement of cotton cultivars.

Materials and Methods

The seeds of 4 lines, 3 testers, and their 12 F_1 hybrids were sown in a randomized complete block design (RCBD) with three replications at the Experimental field of the Department of Plant Breeding and Genetics, Sindh Agriculture University, Tandojam, during Kharif 2019. Details of lines, testers, and F_1 hybrids are presented in the following manner (Table 1). The sowing season for cotton in Pakistan usually starts in April and extends through May. Daytime temperatures often range from 34 to 40 °C. The humidity level is around 62 to 68% varying in time. The fiber testing has been performed at a volume instrument situated at the Department of Textile, TTQC lab in BUITEMS, Quetta. The fiber staple length (mm) has been determined at the USTER HVI 1000 and Fibro graph testing machine. Fig. 1 shows the different seeds of cotton fibers before the testing. As shown in Fig. 2, high-volume instruments provide automated solutions for the cotton industry. They allow for the efficient and cost-effective processing of large batches of cotton, including sorting and grinning. High-volume tools use sensors and automated systems to measure, detect, and control various parameters in the production process.

Fig. 1. Cotton bolls of different seeds, (a) lines, (b) male parents, (c) female parents.

Table 1. Details of lines, testers, and F1 hybrids

Lines	Testers		
	FH-901	**Koonj**	**CIM-602**
CRIS-134	CRIS-134 × FH-901	CRIS-134 × Koonj	CRIS-134 × CIM-602
Mehran	Mehran × FH-901	Mehran × Koonj	Mehran × CIM-602
Sindh-1	Sindh-1 × FH-901	Sindh-1 × Koonj	Sindh-1 × CIM-602
CRIS-342	CRIS-342 × FH-901	CRIS-342 × Koonj	CRIS-342 × CIM-602

Source: Self-made

Fig. 2. Uster HVI Fiber testing machine for staple length.

For Estimation of Both, Heterosis and Combining Ability, the Following Characters were used

2.1. Days to 1st squaring

The number of days was counted from the sowing date to the formation of the first squaring and recorded as days to 1st squaring.

2.2. Days to 1st boll formation

The number of days was counted from the sowing date to the formation of 1st boll of tagged plants and recorded as days to 1st boll formation.

2.3. Boll opened 90 days after sowing

The number of bolls opened 90 days after sowing was counted from tagged plants.

2.4. Number of sympodial branches plant^{-1}

The selected plants (reproductive) or sympodial branches per plant were counted.

2.5. Number of bolls plant^{-1}

The total number of bolls per plant was counted at maturity.

2.6. Boll weight (g)

The average boll weight (gr) of tagged plants was calculated in the laboratory on an electronic weight.

2.7. Seed cotton yield plant^{-1} (g)

Seed cotton from every indexed genotype was picked and weighed in grams. Then, it was recorded separately in the laboratory on an electronic balance.

2.8. 100 – Seed weight (g)

After ginning, one hundred seeds were taken randomly from each selected plant; weight (g) was recorded on electric balance.

2.9. Ginning outturn (%)

The seed cotton of each randomly selected plant was ginned separately and their lint was measured. The formula for ginning out the turn percentage is given below:

$$G.O.T\,\% = \frac{Weight\ of\ lint(g)}{Weight\ of\ seed\ cotton\ (g)} \times 100$$

2.10. Staple length (mm)

The quality of cotton is greatly influenced by staple length, which is a key factor. Staple length is associated with both the fineness and tensile strength of the fibers. In simpler terms, longer staples are usually finer and stronger than shorter ones. To measure staple length, a beard of cotton fiber samples was created. This involved selecting fibers held in a clamp, examining them, and brushing them to straighten and align the fibers. The length of the staples was then measured using a fibro graph, specifically at a 2.5% span length. In this context, 2.5% span length means that at least 2.5% of all fibers are longer than this value. Similarly, 50% span length indicates that at least 50% of all fibers have a length greater than this value.

2.11. Statistical Analysis

The collected data was subjected to the statistical analysis of variance adopted (16), whereas heterosis (17). Combining abilities were estimated (18) and adopted (19).

Results

3.1. Analysis of Variance

The mean square of analysis of variance showed that genotypes, parents, crosses, parents v/s crosses, lines, testers, and line × testers remained significant for most traits like days to 1st squaring and days to 1st boll formation. For example, bolls opened 90 days after sowing, sympodial branches plant^{-1}, bolls plant^{-1}, boll weight, seed cotton yield plant^{-1}, 100 seed weight, ginning out turn, and staple length (Table 2 and 3). However, among them, lines and testers were non-significant for boll opened at 90 days after sowing, whereas the parents were non-significant for boll weight, 100 seed weight, and staple length despite in Fig. 3.

3.2. Mean Performance of Cotton Genotypes

The mean performance of the 10 characters for different lines, testers, and hybrids of cotton genotypes is presented in Tables 4 and 5.

Table 2. Mean squares from analysis of variance for various characters 'resultant from three testers and four lines of cotton genotypes

Source of variation	D.F	Days to 1st squaring	Days to 1st boll formation	Bolls opened 90 days after sowing	Sympodial branches plant^{-1}	Bolls plant^{-1}
Replication	02	0.85	0.21	14.75	5.69	3.00
Genotypes	18	37.40**	26.75**	14.53**	23.23**	58.45**
Parents (P)	6	20.76**	20.60**	23.80**	24.19**	80.88**
Crosses (C)	11	46.17**	31.94**	7.90**	9.48**	41.28**
P vs C	1	40.81**	6.55**	31.74**	168.72**	112.84**
Lines (L)	3	71.88**	62.70**	6.91$^{n.s}$	19.07**	113.65**
Testers (T)	2	13.88**	15.86**	5.44$^{n.s}$	2.33**	42.75**
L × T	6	44.08**	20.89**	9.22$^{n.s}$	7.07**	4.60**
Error	36	0.74	0.93	5.37	0.77	1.25

** = Significant at 1% probability level n.s. = non-significant

Table 3. Mean squares from analysis of variance for various characters' resultant from three testers and four lines of cotton genotype s

Source of variation	D.F	Boll weight	Seed cotton yield plant^{-1}	100 Seed weight	Ginning outturn	Staple length
Replication	02	0.08	452.72	0.13	1.41	0.38
Genotypes	18	0.38**	1777.78**	3.95**	12.02**	4.05**
Parents (P)	6	0.10$^{n.s}$	646.73**	0.02$^{n.s}$	17.56**	0.93$^{n.s}$
Crosses (C)	11	0.19**	847.51**	2.04**	3.66**	3.09**
P vs C	1	3.57**	18796.87**	48.59**	70.65**	33.28**
Lines (L)	3	0.04**	884.19**	2.09**	3.89**	2.10**
Testers (T)	2	0.04**	512.96**	0.66**	4.00**	1.45**
L × T	6	0.31**	940.69**	2.48**	3.44**	4.13**
Error	36	0.01	67.27	0.03	1.16	0.63

** = Significant at 1% probability level n.s. = non-significant

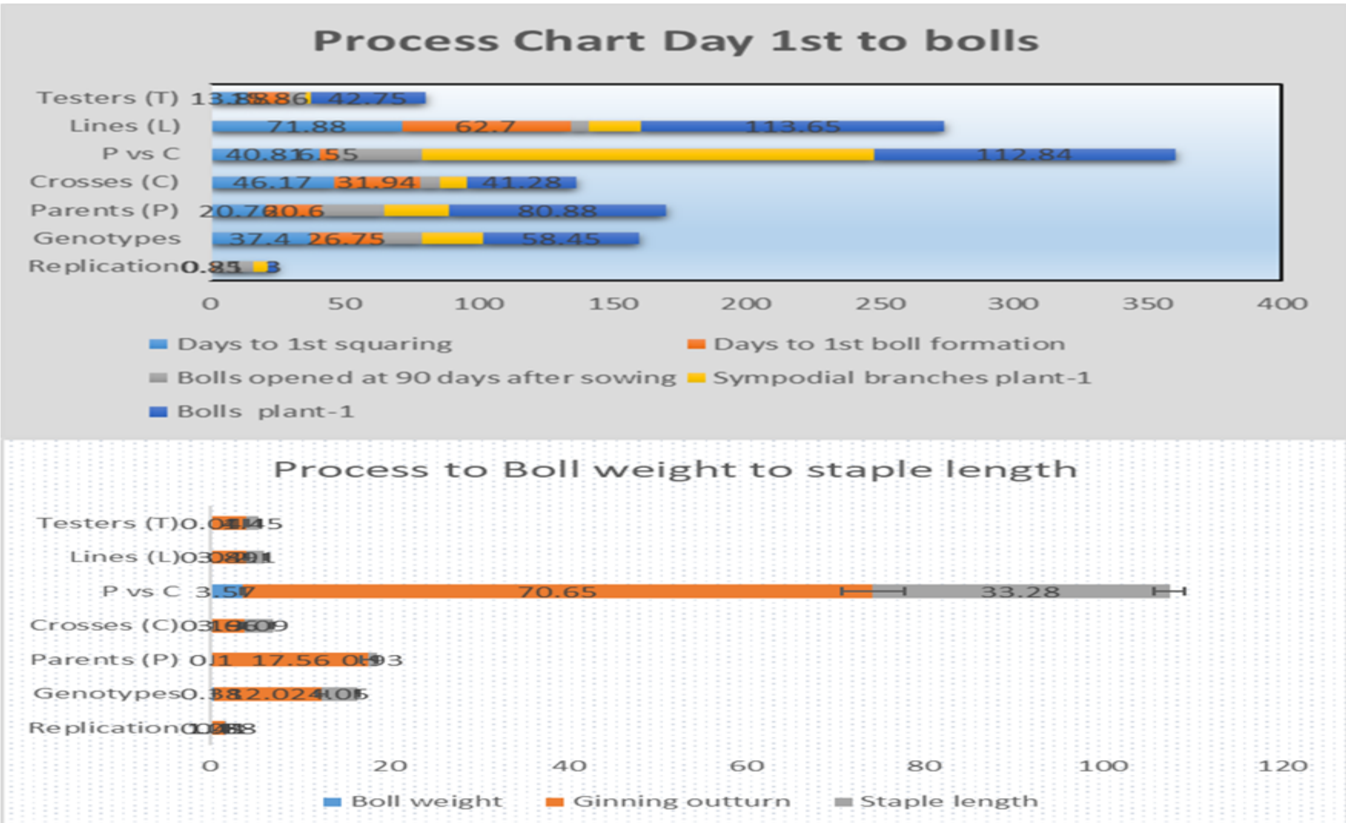

Fig. 3. Cotton growth stages comparison, (a) Growing stages, (b) Development stages

Fig. 4. shows the original plant and field picture after the sowing of the seeds in the field.

The mean performance of lines, testers, and F_1 hybrids exhibited that the parent (line) CRIS-134 took a minimum (of 36.00 days) and (tester) Koonj also recorded a minimum (of 40.00 days) for days to 1st squaring. Table 4 shows that among the hybrids, Mehran × FH-901 and CRIS-134 × CIM-602 took a minimum (34.67 to 35.33 days) for 1st squaring respectively, as seen in Fig. 5. The results for days to 1st boll formation suggested that the lines Sindh-1 recorded a minimum (42.66 days) for boll formation followed by CRIS-134 (45.00) and tester Koonj took a minimum (48.00 days) for days to 1st boll formation as defined in Fig. 4. The F_1 hybrids Mehran × FH-901 (41.66 days) and CRIS-134 × CIM-602 (42.66 days) needed fewer days for boll formation among the hybrids despite the values of Table 4.

The data regarding bolls opened 90 days after sowing showed a maximum (13.00) number of bolls opened by line Sindh-1 and tester FH-901 (10.46). However, line CRIS-134 and tester Koonj gave a minimum (5.66 and 5.46) number of bolls opened 90 days after sowing respectively. While the F_1 hybrids Sindh-1 × CIM-602 gave a maximum (12.33) followed by Mehran × CIM-602 (12.00) and minimum (7.00) bolls opened at 90 days was found in hybrid Mehran × Koonj as despite the values of Table 4. The maximum (25.33 and 20.00) number of sympodial branches plant^{-1} were counted from line Sindh-1 and tester CIM-602 while CRIS-342 and FH-901 gave minimum (21.40 and 17.13) number of sympodial components plant^{-1} respectively. Fig. 4, among the F_1 hybrids, CRIS-342 × Koonj and CRIS-342 × CIM-602 gave the maximum (with 27.00 each) of several sympodial branch's plant$^{-1,}$ respectively. At the same time, CRIS-342 × FH-901 produced the minimum (21.00) for this trait among the F_1 hybrids despite the values of Table 4.

The data regarding bolls plant^{-1} showed that line CRIS-342 and tester FH-901 recorded a maximum (58.00 and 62.33) number of bolls plant^{-1} respectively. However, line Sindh-1 and tester Koonj gave a minimum (50.00 and 46.66) number of bolls plant^{-1} respectively. While F_1 hybrids CRIS-134 × CIM-602 gave a maximum (of 61.66) followed by CRIS-342 × CIM-602 (61.00), the number of bolls plant^{-1} and CRIS-342 × FH-901 and CRIS-134 × Koonj both hybrids recorded minimum (51.00) bolls plant^{-1} among the combinations as despite the Table 4. The mean performance for boll weight showed that line CRIS-134 and tester Koonj gave maximum (2.99 and 2.91 g) boll weight while line Sindh-1 and tester FH-901 gave minimum (2.48 and 2.58 g) boll weight respectively. However, in F_1 hybrids, CRIS-342 × FH-901 recorded a maximum (3.90 g) boll weight while CRIS-134 × FH-901 gave a minimum (3.00 g) boll weight among the hybrids in Table 5.

Line CRIS-342 and tester FH-901 gave maximum (164.77 and 161.38 g) seed cotton yield plant^{-1}, whereas line Sindh-1 and tester Koonj gave minimum (124.21 and 135.77 g) seed cotton yield plant^{-1} respectively. Among the F_1 hybrids, CRIS-134 × CIM-602 shows a maximum (213.76 g) followed by Sindh-1 × FH-901 (204.50 g) seed cotton yield plant^{-1}. While minimum (158.16 g) seed cotton yield was observed in CRIS-134 × Koonj in Fig. 6. The data regarding seed index showed that the line CRIS-134 gave a high (5.92 g) and tester Koonj (5.95 g) seed index among lines and testers. Fig. 5. Even though among the F_1 hybrids, CRIS-342 × FH-901, produced a high (9.13 g) followed by CRIS-342 × Koonj (8.56 g) seed index and CRIS-134 × Koonj gave a minimum (6.40 g) 100 seed weight.

The data regarding GOT, the line CRIS-134 and tester Koonj gave maximum (37.79 and 39.62%) GOT, while CRIS-342 and tester CIM-602 gave minimum (34.95 and 32.70%) GOT respectively. However, Table 5 shows that among the F_1 hybrids CRIS-134 × Koonj gave a maximum (41.00%) followed by CRIS-342 × CIM-602 (39.16%) GOT, and a minimum (36.83%) was found in hybrid Sindh-1 × FH -901. The mean performance for staple length exhibited that line CRIS-342 and tester FH-901 gave maximum (28.00 and 28.16 mm) staple length, while CRIS-134 and tester CIM-602 showed minimum (26.50 and 27.33 mm) staple length respectively. The F_1 hybrids, Mehran × CIM-602 and CRIS-134 × CIM-602 gave maximum higher (31.16 and 31.00 mm) staple length, and minimum (28.00 mm) staple length was found in hybrid CRIS-342 × FH-901 in Fig. 6.

Fig. 4. Cotton plant field, (a) Rows of plant, (b) Individual plant.

Table 4. Mean performance of lines, testers, and F_1 hybrids for various cotton genotype characters

Lines and testers	Days to 1st squaring	Days to 1st boll formation	Bolls opened 90 days after sowing	Sympodial branches plant^{-1}(cm)	Bolls plant^{-1}
CRIS-134	36.00	45.00	5.66	24.00	51.66
Mehran	40.33	46.66	6.00	22.00	55.00
Sindh-1	36.00	42.66	13.00	25.33	50.00
CRIS-342	38.00	45.33	8.60	21.40	58.00
FH-901	41.00	49.00	10.46	17.13	62.33
Koonj	40.00	48.00	5.46	19.00	46.66
CIM-602	43.00	50.33	9.00	20.00	54.33
Average	**39.19**	**46.41**	**8.31**	**21.26**	**53.99**
F_1 hybrids					
CRIS-134 × FH-901	36.00	44.00	8.66	24.66	56.00
Mehran × FH-901	34.67	41.66	9.66	24.00	55.00
Sindh-1 × FH-901	40.00	45.66	11.00	24.33	59.00
CRIS-342 × FH-901	40.00	48.00	11.33	21.00	51.00
CRIS-134 × Koonj	41.66	48.00	9.00	25.00	51.00
Mehran × Koonj	43.00	48.00	7.00	23.00	54.00
Sindh-1 × Koonj	45.00	50.00	10.33	25.00	57.66
CRIS-342 × Koonj	45.33	50.66	8.00	27.00	60.33
CRIS-134 × CIM-602	35.33	42.66	10.00	26.33	61.66
Mehran × CIM-602	44.00	51.00	12.00	26.66	56.00
Sindh-1 × CIM-602	45.66	51.33	12.33	24.00	60.33
CRIS-342 × CIM-602	40.66	48.00	9.00	27.00	61.00
Average	**40.94**	**47.41**	**9.85**	**24.83**	**56.91**
LSD at 5%	**1.43**	**1.59**	**3.83**	**1.45**	**1.85**

Table 5. Mean performance of lines, testers, and F1 hybrids for various cotton genotype characters

Lines and testers	Boll weight (g)	Seed cotton yield plant^{-1} (g)	100 Seed weight (g)	Ginning outturn (%)	Staple length (mm)
CRIS-134	2.99	154.57	5.92	37.79	26.50
Mehran	2.86	157.53	5.88	37.74	27.16
Sindh-1	2.48	124.21	5.89	35.57	27.33
CRIS-342	2.84	164.77	5.69	34.95	28.00
FH-901	2.58	161.38	5.73	34.08	28.16
Koonj	2.91	135.77	5.95	39.62	27.66
CIM-602	2.73	148.66	5.84	32.70	27.33
Average	**2.77**	**149.55**	**5.84**	**36.06**	**27.44**
F_1 hybrids					
CRIS-134 × FH-901	3.00	168.03	6.43	38.50	28.50
Mehran × FH-901	3.50	192.46	7.26	38.50	28.60
Sindh-1 × FH-901	3.46	204.50	8.10	36.83	29.00
CRIS-342 × FH-901	3.90	198.86	9.13	38.00	28.00
CRIS-134 × Koonj	3.10	158.16	6.40	41.00	28.50
Mehran ×Koonj	3.06	165.60	7.23	39.00	29.16
Sindh-1 × Koonj	3.33	192.23	8.20	38.50	28.16
CRIS-342 × Koonj	3.13	189.03	8.56	38.16	28.83
CRIS-134 × CIM-602	3.46	213.76	8.46	37.16	31.00
Mehran × CIM-602	3.13	175.56	7.70	37.16	31.16
Sindh-1 × CIM-602	3.20	193.10	7.73	38.50	29.00
CRIS-342 × CIM-602	3.20	195.13	7.90	39.16	28.50
Average	**3.28**	**187.20**	**7.75**	**38.37**	**29.03**
LSD at 5%	**0.21**	**13.58**	**0.30**	**1.79**	**1.32**

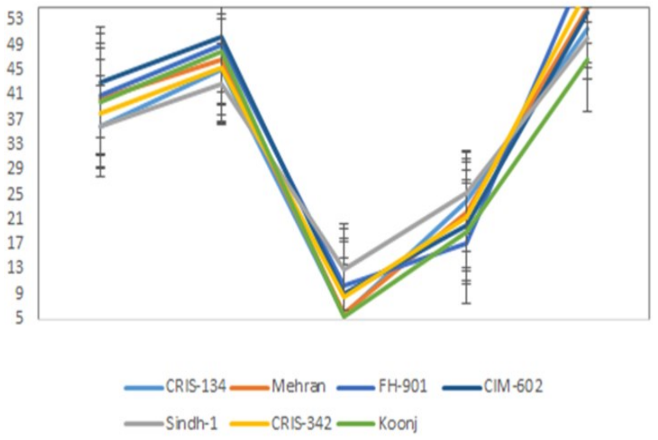

Fig. 5. All seeds growing performance index (Squaring to Bolls plant).

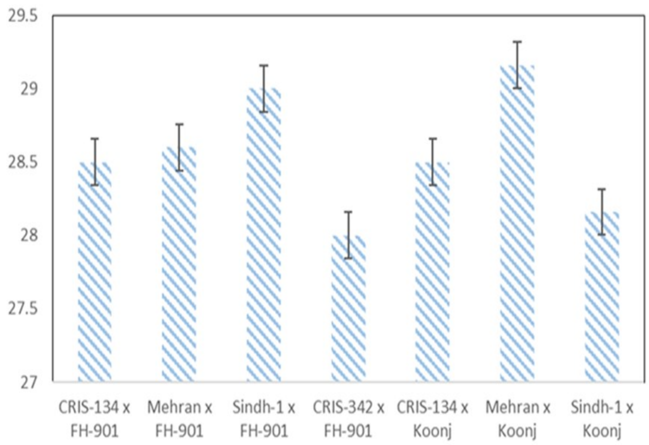

Fig. 6. All types of seeds perform concerning Staple length.

3.3. Heterosis

The heterotic effects of F_1 hybrids for Yield and Yield contributing characters presented in Tables 6 to 16 results are described as under.

Table 6. Effects of F_1Hybrids for Yield and Yield Contributing

F_1 hybrids	Days to 1st squaring	
	M.P (%)	B.P (%)
CRIS-134 × FH-901	-6.49	-12.19
Mehran × FH-901	-16.37	-17.07
Sindh-1 × FH-901	3.89	-2.43
CRIS-342 × FH-901	1.26	-2.43
CRIS-134 × Koonj	9.65	4.17
Mehran × Koonj	7.07	6.62
Sindh-1 × Koonj	18.42	12.50
CRIS-342 × Koonj	16.23	13.32
CRIS-134 × CIM-602	-10.55	-17.83
Mehran × CIM-602	5.61	2.32
Sindh-1 × CIM-602	15.62	6.20
CRIS-342 × CIM-602	0.39	-5.44

MP=Mid parent heterosis, BP=Better parent heterosis.

The top three scorers for negative heterosis were CRIS-134 × FH-901, Mehran × FH-901, and CRIS-134 × CIM-602 they recorded (-6.49,-16.37, and -10.55%) relative heterosis and (-12.19, -17.07 and -17.83%) heterobeltiosis respectively for days to 1st squaring. The maximum heterotic effects among the hybrid ranged from 13.32 to 18.42% (Fig. 6). The F_1 hybrid Sindh-1 × Koonj gave maximum (18.42%) relative heterosis, followed by CRIS-342 × Koonj (16.23%) for the trait. While CRIS-342 × Koonj also gave the highest (13.32%) heterobeltiosis, followed by Sindh-1 × Koonj (12.50%) for days to 1st squaring. The hybrid CRIS-342 × CIM-602 and Mehran × CIM-602 gave minimum (0.39 and 2.32%) relative and heterobeltiosis for the trait respectively. The relative heterosis and heterobeltiosis of F_1 hybrids for days to 1st boll formation are summarized in Fig. 6. The relative heterosis for days to 1st boll formation varied from 10.41 to -12.89%, while heterobeltiosis ranged from 5.54 to -15.23%. Positive heterosis was observed in 6 crosses. Among the hybrids, CRIS-134 × CIM-602, Mehran × FH-901, and CRIS-134 × FH-901 gave higher negative (-10.49,-12.89 and -6.38%) mid-parent heterosis and (-15.23, -14.97 and -10.20%) better parent heterosis for the trait days to 1st boll formation respectively. Whereas Sindh-1 × CIM-602 and CRIS-342 × Koonj produced maximum (10.41 and 5.54%) mid and better parent heterosis for the trait respectively and CRIS-342 × CIM-602 and Sindh-1 × CIM-602 gave minimum positive (0.35 and 0.01) for mid and better parent heterosis for the quality respectively.

The relative heterosis and heterobeltiosis of F_1 hybrids for bolls opened 90 days after sowing is depicted in Fig. 6. The positive relative heterosis for bolls opened 90 days after sowing varied from 2.27 to 61.87%, while positive heterobeltiosis ranged from 0.00 to 59.01%. Among the hybrids, CRIS-134 × Koonj exhibited maximum (61.87%) relative heterosis, while decreased heterotic effects were observed in Sindh-1 × FH-901 (-6.22%). Maximum (59.01%) heterobeltiosis was recorded in CRIS-134 × Koonj. However, minimum (8.31%) effects of heterobeltiosis were observed in the cross CRIS-342 × FH-901 for the trait bolls opened 90 days after sowing. Sympodial branches plant^{-1} and its heterotic effects are presented in Table 8, which exhibited all the hybrids expressed positive relative and heterobeltiosis effects except one. The maximum (33.66 and 26.16%) mid and better parent heterosis was given by CRIS-342 × Koonj, followed by CRIS-342 × CIM-602 (30.43 and 26.16%) for sympodial branches plant^{-1} respectively. Nonetheless, Sindh-1 × CIM-602 and CRIS-134 × FH-901 exhibited minimum (5.91 and 2.75%) mid-parent and better-parent heterosis respectively, for the trait.

The information for heterotic effects of F_1 hybrids regarding the number of bolls plant^{-1} is presented in (Fig 6) the relative positive heterosis for bolls plant^{-1} was observed in 6 crosses which varied from (2.45 to 19.30%) mid-parent and 1.81 to 15.32% for better parent heterosis. The maximum (19.30 and 15.32%) mid and better parent heterosis was given by Sindh-1 × Koonj, followed by CRIS-134 × CIM-602 (16.36 and 13.49%) mid and better parent heterosis for the trait respectively. At the same time, Mehran × CIM-602 displayed minimum (2.45 and 1.81%) mid-parent and better-parent heterosis respectively, for bolls plant^{-1}.

Table 7. Heterotic effects of F_1 hybrids over their mid-parent and better parent for days to 1st squaring of cotton genotypes

F_1 hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Midparent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	36.00	41.00	38.50	36.00	-6.49	-12.19
Mehran × FH-901	40.33	41.00	40.66	34.00	-16.37	-17.07
Sindh-1 × FH-901	36.00	41.00	38.50	40.00	3.89	-2.43
CRIS-342 × FH-901	38.00	41.00	39.50	40.00	1.26	-2.43
CRIS-134 × Koonj	36.00	40.00	38.00	41.67	9.65	4.17
Mehran × Koonj	40.33	40.00	40.16	43.00	7.07	6.62
Sindh-1 × Koonj	36.00	40.00	38.00	45.00	18.42	12.50
CRIS-342 × Koonj	38.00	40.00	39.00	45.33	16.23	13.32
CRIS-134 × CIM-602	36.00	43.00	39.50	35.33	-10.55	-17.83
Mehran × CIM-602	40.33	43.00	41.66	44.00	5.61	2.32
Sindh-1 × CIM-602	36.00	43.00	39.50	45.67	15.62	6.20
CRIS-342 × CIM-602	38.00	43.00	40.50	40.66	0.39	-5.44

Table 8. Heterotic effects of F_1 hybrids over their mid parent and better parent for days to 1st boll formation of cotton genotype

F_1 hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Mid parent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	45.00	49.00	47.00	44.00	-6.38	-10.20
Mehran × FH-901	46.66	49.00	47.83	41.66	-12.89	-14.97
Sindh-1 × FH-901	42.66	49.00	45.83	45.66	-0.37	-6.81
CRIS-342 × FH-901	45.33	49.00	47.16	48.00	1.78	-2.04
CRIS-134 × Koonj	45.00	48.00	46.50	48.00	3.22	0.00
Mehran × Koonj	46.66	48.00	47.33	48.00	1.41	0.00
Sindh-1 × Koonj	42.66	48.00	45.33	50.00	10.33	4.16
CRIS-342 × Koonj	45.33	48.00	46.66	50.66	8.57	5.54
CRIS-134 × CIM-602	45.00	50.33	47.66	42.66	-10.49	-15.23
Mehran × CIM-602	46.66	50.33	48.49	51.00	5.17	1.33
Sindh-1 × CIM-602	42.66	50.33	46.49	51.33	10.41	0.01
CRIS-342 × CIM-602	45.33	50.33	47.83	48.00	0.35	-4.62

Table 9. Heterotic effects of F_1 hybrids over their mid-parent and better parent for bolls opened at 90 days after sowing of cotton genotypes

F_1 hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Mid parent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	5.66	10.46	8.06	8.66	7.44	-17.20
Mehran × FH-901	6.00	10.46	8.23	9.66	17.37	-7.64
Sindh-1 × FH-901	13.00	10.46	11.73	11.00	-6.22	-15.38
CRIS-342 × FH-901	8.60	10.46	9.53	11.33	18.88	8.31
CRIS-134 × Koonj	5.66	5.46	5.56	9.00	61.87	59.01
Mehran × Koonj	6.00	5.46	5.73	7.00	22.16	16.66
Sindh-1 × Koonj	13.00	5.46	9.23	10.33	11.91	-20.53
CRIS-342 × Koonj	8.60	5.46	7.03	8.00	13.79	-6.97
CRIS-134 × CIM-602	5.66	9.00	7.33	10.00	36.42	11.11
Mehran × CIM-602	6.00	9.00	7.50	12.00	60.00	33.33
Sindh-1 × CIM-602	13.00	9.00	11.00	12.33	12.09	-5.15
CRIS-342 × CIM-602	8.60	9.00	8.80	9.00	2.27	0.00

Table 10. Heterotic effects of F_1 hybrids over their mid parent and better parent for sympodial branches plant^{-1} of cotton genotypes

F_1 hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Mid parent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	24.00	17.13	20.56	24.66	19.94	2.75
Mehran × FH-901	22.00	17.13	19.56	24.00	22.69	9.09
Sindh-1 × FH-901	25.33	17.13	21.23	24.33	14.60	-3.94
CRIS-342 × FH-901	21.40	17.13	19.26	21.00	9.03	-1.86
CRIS-134 × Koonj	24.00	19.00	21.50	25.00	16.27	4.16
Mehran × Koonj	22.00	19.00	20.50	23.00	12.19	4.54
Sindh-1 × Koonj	25.33	19.00	22.16	25.00	12.81	-1.30
CRIS-342 × Koonj	21.40	19.00	20.20	27.00	33.66	26.16
CRIS-134 × CIM-602	24.00	20.00	22.00	26.33	19.68	9.70
Mehran × CIM-602	22.00	20.00	21.00	26.66	26.95	21.18
Sindh-1 × CIM-602	25.33	20.00	22.66	24.00	5.91	-5.25
CRIS-342 × CIM-602	21.40	20.00	20.70	27.00	30.43	26.16

Table 11. Heterotic effects of F_1 hybrids over their mid parent and better parent for bolls plant^{-1} of cotton genotypes

F_1 hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Mid parent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	51.66	62.33	56.99	56.00	-1.73	-10.15
Mehran × FH-901	55.00	62.33	58.66	55.00	-6.23	-11.75
Sindh-1 × FH-901	50.00	62.33	56.16	59.00	5.05	-5.34
CRIS-342 × FH-901	58.00	62.33	60.16	51.00	-15.22	-18.17
CRIS-134 × Koonj	51.66	46.66	49.16	51.00	3.74	-1.27
Mehran × Koonj	55.00	46.66	50.83	54.00	6.23	-1.81
Sindh-1 × Koonj	50.00	46.66	48.33	57.66	19.30	15.32
CRIS-342 × Koonj	58.00	46.66	52.33	60.33	15.28	4.01
CRIS-134 × CIM-602	51.66	54.33	52.99	61.66	16.36	13.49
Mehran × CIM-602	55.00	54.33	54.66	56.00	2.45	1.81
Sindh-1 × CIM-602	50.00	54.33	52.16	60.33	15.66	11.04
CRIS-342 × CIM-602	58.00	54.33	56.16	61.00	8.61	5.17

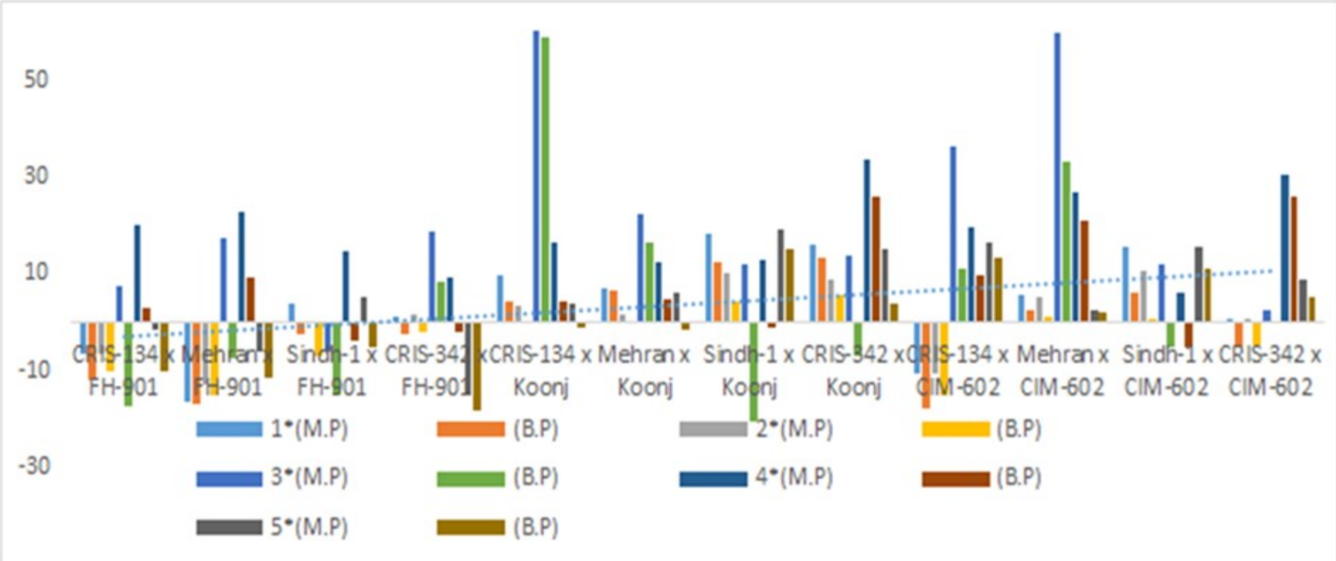

Fig. 7. Performance comparison of all types of seeds from squaring to boll growth.

Furthermore, the information for heterotic effects of 12 F_1 hybrids regarding the boll weight is presented in Table 10, which shows the relative heterosis for this trait. Positive heterosis was observed in all crosses. Among the F_1 hybrids, CRIS-342 × FH-901 exhibited maximum (43.91 and 37.32%) for mid-parent and better parent heterosis, while Mehran × Koonj and CRIS-134 × FH-901 produced minimum (6.25 and 0.33%) for the trait respectively.

The heterotic effect of F1 hybrids over their mid and better parent for seed cotton yield plant^{-1} (Table 11) shows that all 12 combinations exhibited considerable relative heterosis and heterobeltiosis. However, the relative heterosis varied from 6.36 to 47.88% and 2.32 to 41.58% for heterobeltiosis for seed cotton yield. The maximum (47.88 and 41.58%) mid and better parent heterosis was given by Sindh-1 × Koonj, followed by Sindh-1 × Fh-901 and CRIS-134 × CIM-602 (43.2 and 38.2%) mid and better parent heterosis respectively. In comparison, CRIS-134 × FH-901 and CRIS-134 × Koonj produced minimum (6.36 and 2.32%) mid and better parent heterosis respectively, for the Heterotic effect of F_1 hybrids over their mid and better parent for 100 seed index is shown in Table 12. The result shows that all 12 combinations exhibited a considerable amount of heterosis. However, the relative heterosis varied from 7.92 to 59.89%, while heterobeltiosis effects ranged from 7.56 to 59.33%. For CRIS-342 × FH-901 gave the maximum (59.89 and 59.33%) mid and better parent. At the same time, minimum (7.92 and 7.56%) mid and better parent heterosis was found in CRIS-134 × Koonj for seed index respectively.

The calculation regarding the heterotic effect of F_1 hybrids over their mid and better parent for ginning outturn (Table 13) shows that the impact of relative heterosis varied from 0.82 to 15.75%. In contrast, heterobeltiosis effects ranged from 12.04 to -3.68. It was also observed that CRIS-342 × CIM-602 produced maximum (15.75 and 12.04%) mid and better parent heterosis for ginning outturn and Mehran × Koonj and CRIS -134 × FH-901 produced minimum (0.82 and 1.87%) mid and better parent the trait respectively.

The heterotic effect of F_1 hybrids over their mid and better parent for staple length in cotton is given in Table 14. The result shows that all combinations exhibited a considerable amount of positive relative heterosis and heterobeltiosis, except for hybrid CRIS-342 × FH-901. The relative heterosis varied from 15.19% to -0.28, while heterobeltiosis effects ranged from 14.01 to -0.56%. The CRIS-134 × CIM-602 and Mehran × CIM-602 produced maximum (15.19 and 14.01%) mid and better heterosis for staple length respectively. Nonetheless, Sindh-1 × Koonj and CRIS-342 × FH-901 gave minimum (2.43 and 1.20%) mid and better parents for the trait.

Table 12. Heterotic effects of F_1 hybrids over their mid parent and better parent for boll weight of cotton genotypes

F_1hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Mid parent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	2.99	2.58	2.78	3.00	7.91	0.33
Mehran × FH-901	2.86	2.58	2.72	3.50	28.67	22.37
Sindh-1 × FH-901	2.48	2.58	2.53	3.46	36.75	34.10
CRIS-342 × FH-901	2.84	2.58	2.71	3.90	43.91	37.32
CRIS-134 × Koonj	2.99	2.91	2.95	3.10	5.08	3.67
Mehran × Koonj	2.86	2.91	2.88	3.06	6.25	5.15
Sindh-1 × Koonj	2.48	2.91	2.69	3.33	23.79	14.43
CRIS-342 × Koonj	2.84	2.91	2.87	3.13	9.05	7.56
CRIS-134 × CIM-602	2.99	2.73	2.86	3.46	20.97	15.71
Mehran × CIM-602	2.86	2.73	2.79	3.13	12.18	9.44
Sindh-1 × CIM-602	2.48	2.73	2.60	3.20	23.07	17.21
CRIS-342 × CIM-602	2.84	2.73	2.78	3.20	15.10	12.67

Table 13. Heterotic effects of F_1 hybrids over their mid parent and better parent for seed cotton yield plant^{-1} of cotton genotypes

F_1 hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Mid parent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	154.57	161.38	157.97	168.03	6.36	4.12
Mehran × FH-901	157.53	161.38	159.45	192.46	20.70	19.25
Sindh-1 × FH-901	124.21	161.38	142.79	204.50	43.21	26.71
CRIS-342 × FH-901	164.77	161.38	163.07	198.86	21.94	20.68
CRIS-134 × Koonj	154.57	135.77	145.17	158.16	8.94	2.32
Mehran × Koonj	157.53	135.77	146.65	165.60	12.92	5.12
Sindh-1 × Koonj	124.21	135.77	129.99	192.23	47.88	41.58
CRIS-342 × Koonj	164.77	135.77	150.27	189.03	25.79	14.72
CRIS-134 × CIM-602	154.57	148.66	151.61	213.76	40.99	38.29
Mehran × CIM-602	157.53	148.66	153.09	175.56	14.67	11.44
Sindh-1 × CIM-602	124.21	148.66	136.43	193.10	41.53	29.89
CRIS-342 × CIM-602	164.77	148.66	156.71	195.13	24.51	18.42

Table 14. Heterotic effects of F_1 hybrids over their mid parent and better parent for 100 seed weight of cotton genotypes

F_1 hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Mid parent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	5.92	5.73	5.82	6.43	10.48	8.61
Mehran × FH-901	5.88	5.73	5.80	7.26	25.17	23.46
Sindh-1 × FH-901	5.89	5.73	5.81	8.10	39.41	37.52
CRIS-342 × FH-901	5.69	5.73	5.71	9.13	59.89	59.33
CRIS-134 × Koonj	5.92	5.95	5.93	6.40	7.92	7.56
Mehran × Koonj	5.88	5.95	5.91	7.23	22.33	21.51
Sindh-1 × Koonj	5.89	5.95	5.92	8.20	38.51	37.81
CRIS-342 × Koonj	5.69	5.95	5.82	8.56	47.07	43.86
CRIS-134 × CIM-602	5.92	5.84	5.88	8.46	43.87	42.90
Mehran × CIM-602	5.88	5.84	5.86	7.70	31.39	30.95
Sindh-1 × CIM-602	5.89	5.84	5.86	7.73	31.91	31.23
CRIS-342 × CIM-602	5.69	5.84	5.76	7.90	37.15	35.27

Table 15. Heterotic effects of F_1 hybrids over their mid parent and better parent for ginning outturn of cotton genotypes

F_1 hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Mid parent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	37.79	34.08	35.93	38.50	7.15	1.87
Mehran × FH-901	37.74	34.08	35.91	38.50	7.21	2.01
Sindh-1 × FH-901	35.57	34.08	34.82	36.83	5.77	3.54
CRIS-342 × FH-901	34.95	34.08	34.51	38.00	10.11	8.72
CRIS-134 × Koonj	37.79	39.62	38.70	41.00	5.94	3.48
Mehran × Koonj	37.74	39.62	38.68	39.00	0.82	-1.56
Sindh-1 × Koonj	35.57	39.62	37.59	38.50	2.42	-2.82
CRIS-342 × Koonj	34.95	39.62	37.28	38.16	2.36	-3.68
CRIS-134 × CIM-602	37.79	32.70	35.24	37.16	5.44	-1.66
Mehran × CIM-602	37.74	32.70	35.22	37.16	5.50	-1.53
Sindh-1 × CIM-602	35.57	32.70	34.13	38.50	12.80	8.23
CRIS-342 × CIM-602	34.95	32.70	33.82	39.16	15.78	12.04

Table 16. Heterotic effects of F_1 hybrids over their mid-parent and better parent for a staple length of cotton genotypes

F_1 hybrids	Female parent	Male parent	Mid parent (M.P)	F_{1s}	Percentage increase (+) or decrease (-) of F_1 over	
					Mid parent (M.P)	Better parent (B.P)
CRIS-134 × FH-901	26.50	28.16	27.33	28.50	4.28	1.20
Mehran × FH-901	27.16	28.16	27.66	28.60	3.39	1.56
Sindh-1 × FH-901	27.33	28.16	27.74	29.00	4.54	2.98
CRIS-342 × FH-901	28.00	28.16	28.08	28.00	-0.28	-0.56
CRIS-134 × Koonj	26.50	27.66	27.08	28.50	5.24	3.03
Mehran × Koonj	27.16	27.66	27.41	29.16	6.38	5.42
Sindh-1 × Koonj	27.33	27.66	27.49	28.16	2.43	1.80
CRIS-342 × Koonj	28.00	27.66	27.83	28.83	3.59	2.96
CRIS-134 × CIM-602	26.50	27.33	26.91	31.00	15.19	13.42
Mehran × CIM-602	27.16	27.33	27.24	31.16	14.39	14.01
Sindh-1 × CIM-602	27.33	27.33	27.33	29.00	6.11	6.11
CRIS-342 × CIM-602	28.00	27.33	27.66	28.50	3.03	1.78

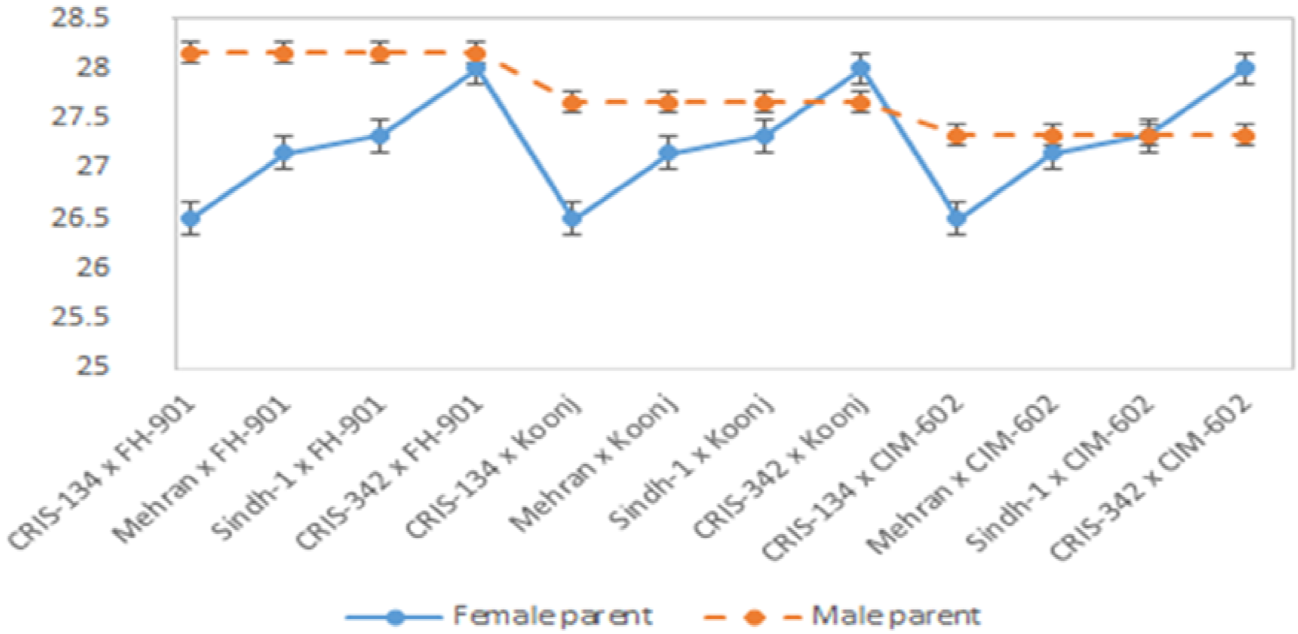

Fig. 8. Growth performance of all types of seeds concerning male to female parents.

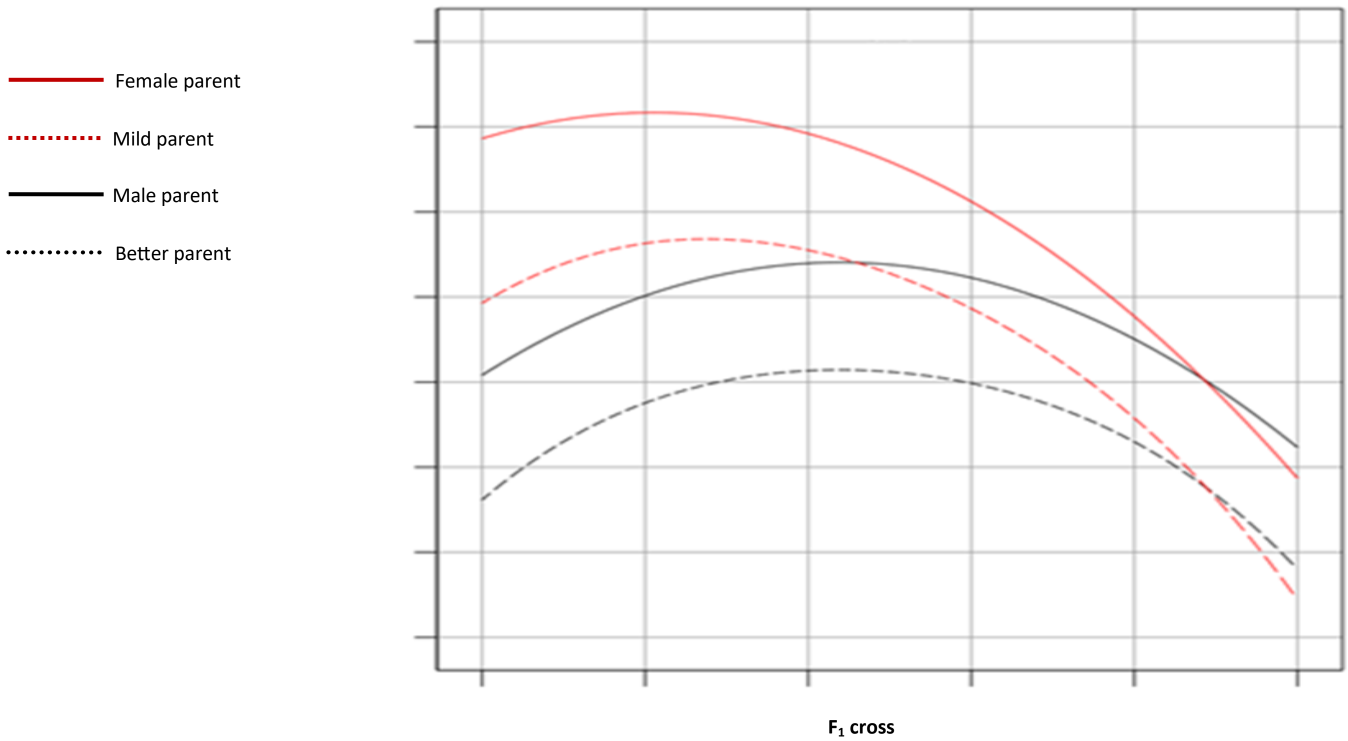

Fig. 9. The coefficient of the staple length increased and decreased concerning different parents.

Fig. 8 and 9 have despite the growth performance of all seeds related to different parents. The female parents are higher enough as compared to male parents, which slightly increased. The mild parent is moderate through estimated growth in Fig. 9. Furthermore, it has revealed the coefficient performance of better and female parents. The maximum increase has been noted at the Mehran cross bread, according to Table 16 and Fig. 8. It has been noted briefly during the research that Sindh-1 and CRIS cross seeds showed a lower decline during the growth regarding staple length.

3.4. Combining Ability Effects

The combining ability effects of lines, testers, and line × testers for various quantitative traits are summarized in Tables 17- 20 and the results are described here as under.

Days to 1st squaring: Among the parents, the maximum hostile general combining ability (GCA) effects (-4.06) were recorded in the line CRIS-134 and (-1.19) in the tester CIM-602 for days to 1st squaring (Table 15). However, hostile specific combining ability (SCA) effects (-5.36) were observed in the hybrid Sindh-1 × CIM-602 (Table 16). While maximum positive GCA effects (2.50) were recorded in the line CRIS-342 and (0.89) in the tester Koonj. While minimum positive GCA effects (0.61) were recorded in line Mehran and (0.31) in the tester FH-901. However, CRIS-134 × CIM-602, followed by Sindh-1 × FH-901, produced maximum (4.31 and 2.81) SCA effects respectively. However, a minimum (0.22) positive SCA effect was given by Mehran × Koonj among the hybrids.

The adverse GCA effects (-3.61) were recorded in the line CRIS-134 and (-1.30) in the tester CIM-602 for days to 1st boll formation (Table 15). The GCA effects for days to 1st boll formation showed that the maximum positive GCA effects (2.73) were recorded in the line CRIS-342 and (0.87) in the tester FH-901. However, adverse specific combining ability effects (-3.70) were observed in the hybrid Sindh-1 × CIM-602 (Table 16). The minimum (0.28) positive GCA effects were recorded in the line Sindh-1 and (0.45) in the tester Koonj. The higher (3.19 and 2.22) SCA effects were given by CRIS-134 × CIM-602 and Sindh-1 × Koonj and minimum (0.02) SCA effects were recorded in CRIS-342 × FH-901 for days to 1st boll formation.

The GCA effects for bolls opened 90 days after sowing. The parents recorded maximum positive (1.25) GCA effects in the line CRIS-342 and (0.72) in the tester FH-901. At the same time, minimum GCA effects (-0.09) were recorded in the line CRIS-134 and (-0.11) in the tester Koonj for bolls opened at 90 days after sowing (Table 15). Concerning the SCA effects, hybrid CRIS-134 × CIM-602 produced a maximum (1.84) value, followed by Mehran × FH-901 (1.50). Nevertheless, negative SCA (-1.83) effects were observed in the hybrid CRIS-134 × FH-901 (Table 16).

The data regarding GCA effects for sympodial branches plant^{-1} showed that among the parents, the maximum positive (1.28) GCA effects were recorded in the line Sindh-1 and (0.33) in the tester CIM-602. In comparison, minimum (0.28) positive GCA effects were recorded in the line Sindh-1 and (0.45) in the tester Koonj for this trait (Table 15). The results further revealed that hybrid Mehran × Koonj produced maximum (1.83) SCA effects followed by CRIS-342 × FH-901(1.25), whereas negative SCA (-2.05) effects were observed in the hybrid CRIS-342 × Koonj (Table 16).

The results regarding GCA effects for bolls plant^{-1} showed that among the parents, the maximum (2.97) positive GCA effects were recorded in the line Sindh-1 and (2.00) in the tester CIM-602. In contrast, minimum positive GCA effects (2.20) were recorded in the line CRIS-342 for bolls plant^{-1} (Table 15). However, the reduced and adverse (-4.91) GCA effects were observed by Mehran. Among the hybrid, CRIS-342 × Koonj produced maximum (1.47) SCA effects followed by CRIS-134 × FH-901 (1.09), whereas the hybrid CRIS-134 × Koonj showed adverse SCA effects (-1.41) (Table 16).

The data regarding GCA effects for boll weight showed that among the parents, the line Mehran and CRIS-134 gave maximum (0.06 and 0.03) GCA effects, respectively, and a value of 0.06 was noted in the Tester FH -901. On the other hand, the minimum (0.02) positive GCA effects were recorded in the line Sindh-1 and (0.01) in the Tester CIM-602 for boll weight (Table 17). However, the reduced and negative GCA (-0.09) effects were observed by CRIS-342. Among the hybrid, CRIS-342 × Koonj produced maximum (1.06) SCA effects. However, negative SCA (-0.38) effects were observed in the hybrid CRIS-134 × FH-901 (Table 18).

Furthermore, GCA effects of seed cotton yield plant^{-1} showed that the line Sindh-1 and Tester CIM-602 gave higher (11.14 and 7.55 respectively) GCA effects among the parents. In contrast, minimum (0.73) positive GCA effects were recorded in the line CRIS-342 for seed cotton yield plant^{-1} (Table 17). However, the reduced and adverse (-12.98) GCA effects were observed by Mehran. The hybrid Mehran × FH-901 produced maximum (28.18) SCA effects for seed cotton yield. However, adverse (-16.77) SCA effects were observed in the hybrid CRIS-134 × FH-901 (Table 18).

The information regarding GCA effects for 100 seed weight exhibited that among the parents, the line Sindh-1 gave maximum (0.65) GCA effects compared to others and (0.16) in the Testers CIM-602. In contrast, minimum positive GCA effects (0.01) were recorded in the line CRIS-342 and (0.10) in the Tester FH-901 for 100 seed weight (Table 17). Furthermore, the reduced and adverse (-0.17) GCA effects were observed by Mehran. The hybrid-like Mehran × FH-901 gave maximum (1.45) SCA effects, whereas adverse (-3.40) SCA effects were observed in the hybrid Mehran × Koonj (Table 18).

The results regarding GCA effects for ginning outturn exhibited that the line Mehran and the Tester Koonj gave maximum (0.96 and 0.67 respectively) GCA effects for this trait (Table 17). However, the minimum negative (-0.43) GCA effects were observed by CRIS-134. Among the hybrids, CRIS-342 × CIM-602 produced maximum (1.22) SCA effects, whereas the CRIS-342 × FH-901 hybrid presented adverse (-0.78) SCA effects (Table 18).GCA effects for staple length showed that among the parents, the line CRIS-342 showed maximum (0.52) GCA effects and (0.38) in the Testers CIM-602, while minimum (0.30) positive GCA effects were recorded in the line Sindh-1 (Table 17). However, the minimum (-0.53) adverse GCA effects were found in Mehran. The F_1 hybrid CRIS-342 × FH-901 recorded maximum (1.69) SCA effects for staple length. However, negative (-1.43) SCA effects were found in the hybrid CRIS-342 × CIM-602 (Table 18).

Figure 10 shows the growth performance of all seeds related to different growth stages. The female is higher enough as compared to testers which slightly increased. The testers are moderate through estimated growth in Table 17. Furthermore, it has revealed the coefficient performance of better and female parents. The maximum increase has been noted at the koonj cross bread according to Table 18 and Fig. 10. It has been noted briefly during the research that Sindh-1 and CRIS-134 cross seeds started lower and declined, but after the growth concerning staple length, some pieces of bread have an excellent coefficient. The liners can increase the coefficient value as they end up growing stages.

Table 17. General combining ability (GCA) effects for various characters of four female lines and three testers of cotton genotypes

Female lines	Days to 1st squaring	Days to 1st boll formation	Bolls opened 90 days after sowing	Sympodial branches plant^{-1}	Bolls plant^{-1}
CRIS-134	-4.06	-3.61	-0.09	-0.50	-0.25
Mehran	0.61	0.62	-0.75	-1.83	-4.91
Sindh-1	0.94	0.28	-0.41	1.28	2.97
CRIS-342	2.50	2.73	1.25	1.05	2.20
S.E (gi)	0.40	0.44	1.09	0.41	0.51
Testers/Pollinators					
FH-901	0.31	0.87	0.72	-0.49	-1.74
Koonj	0.89	0.45	-0.11	0.17	-0.24
CIM-602	-1.19	-1.30	-0.61	0.33	2.00
S.E (gi)	0.34	0.38	0.94	0.34	0.44

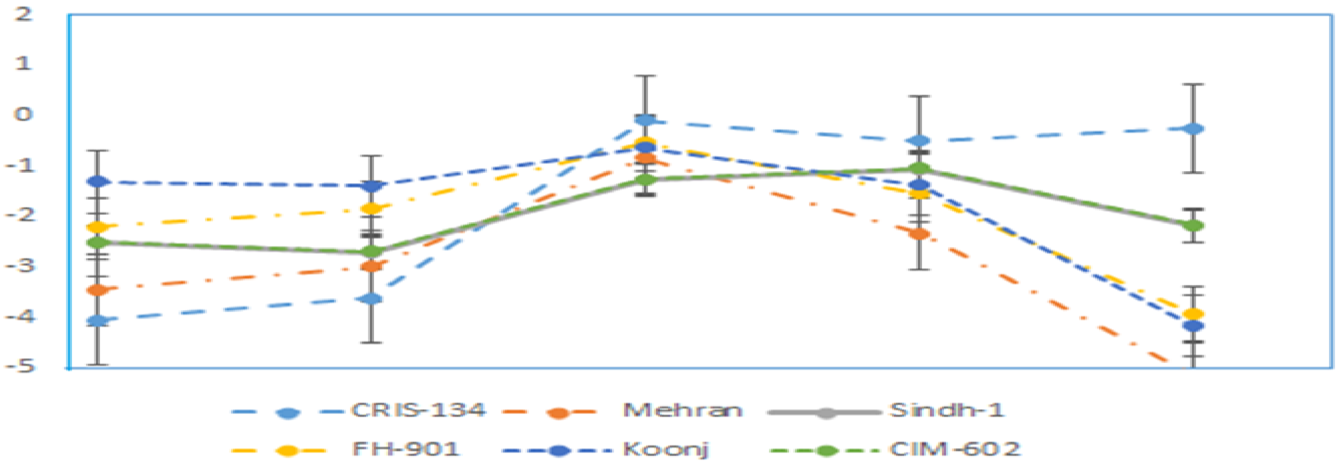

Fig. 10. Coefficient combining ability of female lines vs Testers concerning growing stages.

Table 18. Specific combining ability (SCA) affects estimates from line × tester analysis for various characters in cotton

F_1 hybrids/Crosses	Days to 1st squaring	Days to 1st boll formation	Bolls opened 90 days after sowing	Sympodial branches plant^{-1}	Bolls plant^{-1}
CRIS-134 × FH-901	-1.19	-0.64	-1.83	0.83	1.09
Mehran × FH-901	-1.86	-0.87	1.50	-1.50	0.75
Sindh-1 × FH-901	2.81	1.47	0.17	-0.61	-0.47
CRIS-342 × FH-901	0.25	0.02	0.17	1.25	-1.36
CRIS-134 × Koonj	-3.11	-2.56	0.00	-0.5	-1.41
Mehran × Koonj	0.22	-0.45	0.00	1.83	-0.75
Sindh-1 × Koonj	2.56	2.22	-1.33	0.72	0.70
CRIS-342 × Koonj	1.33	1.22	1.33	-2.05	1.47
CRIS-134 × CIM-602	4.31	3.19	1.84	-0.33	0.34
Mehran × CIM-602	2.64	1.30	-1.50	-0.33	0.00
Sindh-1 × CIM-602	-5.36	-3.70	1.17	-0.11	0.22
CRIS-342 × CIM-602	-1.59	-0.81	-1.50	0.79	-0.11
S.E (si)	0.70	0.78	1.89	0.71	0.91

Table 19. General combining ability (GCA) effects for various characters of four female lines and three testers of cotton genotypes

Female lines	Boll weight	Seed cotton yield plant^{-1}	100 Seed weight	Ginning outturn	Staple length
CRIS-134	0.03	1.13	-0.5	-0.43	-0.33
Mehran	0.06	-12.98	-0.17	0.96	-0.53
Sindh-1	0.02	11.14	0.65	-0.42	0.30
CRIS-342	-0.09	0.73	0.01	-0.09	0.52
S.E (gi)	1.48	3.86	2.58	0.50	0.37
Testers/Pollinators					
FH-901	0.06	-3.52	0.10	-0.32	-0.08
Koonj	-0.05	-4.00	-0.26	0.67	-0.30
CIM-602	0.01	7.55	0.16	-0.32	0.38
S.E (gi)	1.28	3.34	2.23	0.43	0.31

Table 20. Specific combining ability (SCA) affects estimates from line × tester analysis for various characters in cotton

F_1 hybrids/Crosses	Boll weight	Seed cotton yield plant^{-1}	100 Seed weight	Ginning outturn	Staple length
CRIS-134 × FH-901	-0.38	-16.77	-0.83	0.89	-0.12
Mehran × FH-901	0.49	28.18	1.45	-1.00	-0.47
Sindh-1 × FH-901	-0.04	-2.58	-0.31	0.89	-1.09
CRIS-342 × FH-901	-0.06	-8.84	0.17	-0.78	1.69
CRIS-134 × Koonj	0.24	8.14	-2.22	-2.11	0.20
Mehran × Koonj	0.81	-12.04	-3.40	1.00	0.25
Sindh-1 × Koonj	0.88	-5.30	-2.07	-0.45	-0.20
CRIS-342 × Koonj	1.06	9.18	-2.26	-0.44	-0.25
CRIS-134 × CIM-602	0.13	8.62	0.68	-0.78	-0.08
Mehran × CIM-602	-0.30	-16.16	-0.51	0.00	0.23
Sindh-1 × CIM-602	0.14	7.87	-0.11	-0.45	1.29
CRIS-342 × CIM-602	0.01	-0.35	-0.03	1.22	-1.43
S.E (si)	2.58	6.69	0.14	0.87	0.64

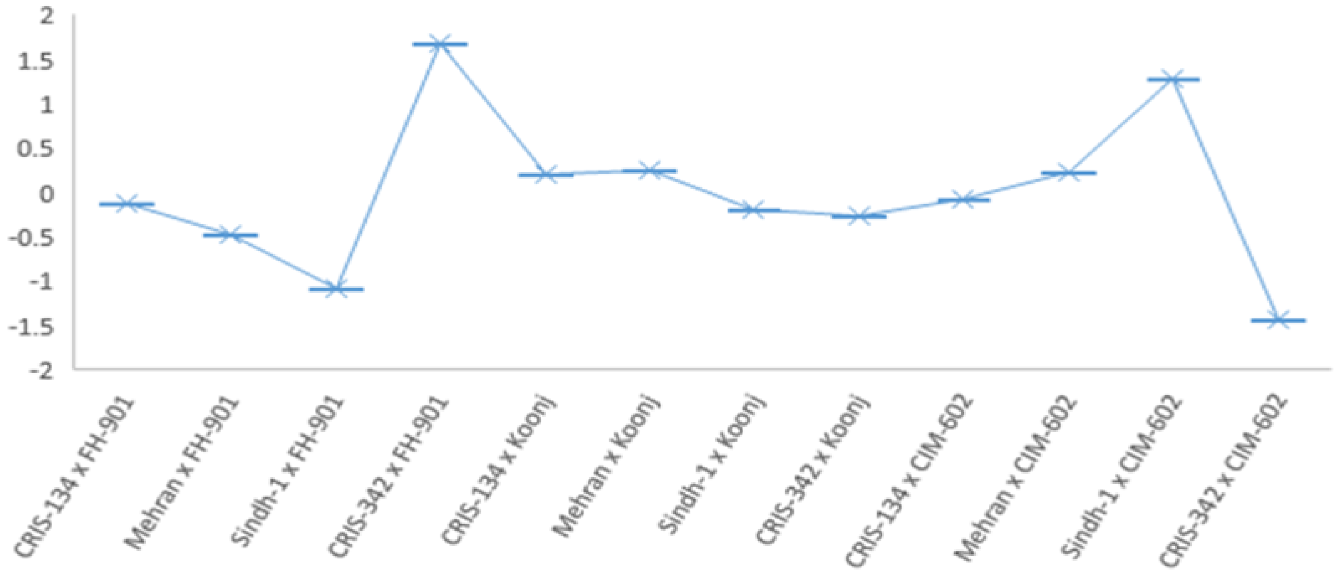

Fig. 11. Estimated combining ability from line × tester F_1 hybrid crosses concerning staple length.

Fig. 11. reveals that all seeds' growth performance is related to different growth stages. The F_1 hybrid is higher enough as compared to others which slightly decreased. The F_1 hybrid is moderate through estimated growth in Table 20. Furthermore, it has revealed the coefficient performance of better and parent's cross pieces of bread. The maximum increase has been noted at the CRIS-342 cross bread with FH-901, according to Table 19. It has been revealed during the experimental values Sindh-1 and CIM-602 cross seeds showed a higher trend. Still, one bread has a moderate coefficient after the growth concerning staple length. The liners can increase the coefficient value as they end up growing stages.

Discussion

A prominent fiber crop in our nation is the cotton plant (*Gossypium hirsutum* L.). Cotton demands an extended cultivation period, abundant sunlight, and ample water throughout its growth phase, followed by dry conditions during the harvesting period (20). Moreover, line × tester analysis (18) provides an efficient method for evaluating GCA and SCA of cotton lines and hybrids (20). line × tester analysis and heterotic effects among the hybrids for different traits, viz: days to 1st squaring, days to 1st boll formation. Bolls opened at 90 days after sowing, Sympodial branches plant^{-1}, Bolls plant^{-1}, Boll weight (g), Seed cotton yield plant^{-1} (g), 100 Seed weight (g), Ginning out turn (%), Staple length (mm) and the way of inheritance of traits mentioned above in F_1 generation as well as the contribution of lines and tester in the expression of the individual characteristics (21).

4.1. Analysis of Variance

Analysis of variance showed the genotypes, parents, crosses, parents vs crosses, lines, testers, and line × testers were significant for most of the traits (Tables 1 and 2). It is shown that substantial genetic differences among lines, testers, and hybrids were present for the studied characters. However, the GCA variances were more significant than SCA variances for most traits, indicating the preponderance of additive variances for controlling the characteristics. It was reported that genotypes were significant for studied traits (22). The significant GCA and SCA variances showed that additive and non-additive variance were significant for governing the attribute; however, the magnitude of non-additive conflict was superior to the additive for most of the traits. Other researchers also reported substantial mean squares of genotypes, lines, and line × testers for various studied features (20, 23).

4.2. Mean Performance of Cotton Genotypes

The mean performance (Tables 3 and 4) showed that CRIS-134 gave minimum days to 1st squaring, staple length, bigger bolls, and more lint % among the lines. Sindh-1 recorded more bolls opening 90 days after sowing and more sympodial branches plant-1, higher seed index, CRIS -342 set more bolls plant and higher seed cotton yield plant^{-1}. Whereas in testers, Koonj counted less number of days for setting 1st squaring, minimum days for 1st boll formation and maximum boll weight, 100-seed weight and FH-901 recorded maximum bolls plant^{-1} and seed cotton yield plant^{-1} and staple length. The hybridization program should utilize these lines and testers to improve these traits further. Among the F_1 hybrids, Mehran × FH-901 showed minimum days to 1st squaring and days to 1st boll formation, Sindh-1 × CIM-602 gave maximum boll opening at 90 days after sowing, CRIS-134 × CIM-602 gave more number of boll plant^{-1}, seed cotton yield plant^{-1} and second scorer for staple length. At the same time, CRIS-342 × Koonj and CRIS-342 × CIM-602, both hybrids, recorded more sympodial branches plant^{-1}. Previous research reported similar types of mean performance for lines, testers, and their F_1 hybrids for earliness, yield, and fiber traits (23, 24).

CRIS-134 exhibited the shortest duration to reach the first squaring stage, possessed longer staple length, larger bolls, and a higher % of lint compared to the other lines (25).

4.3. Heterotic Estimates F_1 Hybrids

The relative heterosis and heterobeltiosis of F_1 hybrids (Tables 5 and 14) showed that hybrid CRIS-134 × FH-901 and Mehran × Fh-901 gave adverse heterotic effects for days to 1st squaring and days to 1st boll formation. Therefore, it is suggested that negative heterosis is desirable for developing short-duration cotton genotypes for phenological traits. Similar results were obtained in another study also recorded negative heterosis for phenological traits (12, 26).

For bolls opened at 90 days after sowing, the hybrids CRIS-134 × Koonj exhibited maximum relative heterosis and heterobeltiosis was given by CRIS-134 × Koonj and CRIS-342 × Koonj for sympodial branches plant^{-1}, Sindh-1 × Koonj for bolls plant^{-1}, CRIS-342 × FH-901 for boll weight and Sindh-1 × Koonj for seed cotton yield plant $^{-1}$. The above hybrids should be suggested for utilization for hybrid crop development in cotton. Similarly, other researchers also reported a similar result of relative heterosis and heterobeltiosis of F_1 hybrids for yield and fiber traits of cotton (27-30).

CRIS-342 × FH-901 displayed maximum heterosis for 100 seed weight and CRIS-342 × CIM-602 gave high heterosis for ginning outturn (%); CRIS-134 × CIM-602 and Mehran × CIM-602 produced high relative heterosis and maximum heterosis for staple length respectively. Studies were mentioned for high relative heterosis and heterobeltiosis for Yield contributing traits and fibre quality parameters of cotton (23, 31-33).

4.4. Combining Ability Estimates

The GCA and SCA effects for phenological, Yield and fiber traits are presented in Tables 17-20, which indicated that among the lines, CRIS-134 gave maximum adverse effects for days to 1st squaring and days to 1st boll formation and next scorer regarding positive GCA effects; Sindh-1 displayed positive GCA effects for sympodial branches plant^{-1}, bolls plant^{-1}, seed cotton yield plant^{-1} and 100-seed weight and CRIS-342 showed higher GCA effects for boll opening at 90 days after sowing and staple length. Among the testers, CIM-602 showed harmful GCA properties for days to 1st squaring and days to 1st boll formation and maximum positive GCA effects for sympodial branches plant^{-1}, bolls plant^{-1}, seed cotton yield plant^{-1}, 100-seed weight and staple length. The findings conclude that line Sindh-1, CRIS-134, and tester CIM-602 should be utilized in the hybridization program to improve these traits. Similarly, studies exhibited significant GCA effects for most of the traits studied and observed the best combiner among 2 lines (11, 20, 22, 23).

The specific combining ability effects showed that the hybrid Sindh-1 × CIM-602 recorded a negative SCA effect for days to 1st squaring and days to 1st boll formation. In addition, maximum positive SCA effects were observed for boll opening at 90 days after sowing in the hybrid CRIS-134 × CIM-602, for bolls plant^{-1} and boll weight in the hybrid CRIS-342 × Koonj, C for seed cotton yield plant^{-1} and 100-seed weight in CRIS-342 × Koonj, whereas CRIS-342 × CIM-602 and CRIS-342 × FH-901 gave high SCA effects for lint % and staple length. Such findings are similar to these studies (34-37), which also estimated the high SCA effects for traits studied.

Within the group of testers, CIM-602 displayed adverse General Combining Ability (GCA) characteristics for both days to 1st squaring and days to 1st boll formation. However, it exhibited the most favorable GCA effects for sympodial branches per plant, bolls per plant, seed cotton yield per plant, 100-seed weight, and staple length. Based on these observations, it is recommended to incorporate line Sindh-1, CRIS-134, and tester CIM-602 into the hybridization program as they show potential for enhancing these traits.

Regarding GCA effects, the significance observed in most of the traits studied for line and tester variance effects suggests the importance of various outcomes for general combinatorial ability (GCA), especially those related to the additive type of gene action responsible for such traits. On the other hand, the significance of the mean squares for the line × tester interaction effect observed in most of the characteristics studied indicates the importance of specific combinatorial ability (SCA), which suggests the significance of genes with non-additive type action. In most cases, mid and better heterosis of two F1 hybrids are discussed for better implementation and less variance while lower and higher results are easier to predict the values.

Conclusion

The following conclusions were drawn.

1. Genotypes, parents, crosses, parent's v/s crosses, lines, testers, and line × testers were significant for most traits studied.

2. Lines and testers were non-significant for boll opened 90 days after sowing, and parents for boll weight, 100 seed weight, and staple length were also non-significant. The northern states of India focus on growing varieties like Bunny, H-777, and RH-74, which will be replaced by lines and testers.
3. States like Gujarat and Maharashtra predominantly cultivate varieties like GJ-29, Gujarat-86, and MRC-7351. The Line CRIS-134, Sindh-1, and tester FH-901 gave a higher mean performance for all the traits. Among the hybrids, Mehran × FH-901, Sindh-1 × CIM-602, CRIS-134 × CIM-602, CRIS-342 × Koonj, and CRIS-342 × CIM-602 gave a desirable mean performance and heterotic effect for all the traits.
4. CRIS-134, Sindh-1, CRIS-342, and tester CIM-602 gave desirable GCA effects for most traits studied.
5. Sindh-1 × CIM-602 gave a negative SCA effect for days to 1st squaring and days to 1st boll formation, and CRIS-134 × CIM-602 showed maximum positive SCA effects for boll opening at 90 days after sowing.
6. Indian region, specific cotton varieties have shown notable performance in various regions. For instance, states like Uttar Pradesh prefer cultivars such as Bunny, H-777, and LRA-5166. Furthermore, in hybrid combinations, CRIS-342 × Koonj demonstrated superior Specific Combining Ability (SCA) effects for bolls per plant, Mehran × FH-901 exhibited higher SCA effects for both 100-seed weight and seed cotton yield per plant, while CRIS-342 × CIM-602 and CRIS-342 × FH-901 showcased notable SCA effects for lint % and staple length respectively.

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Data Availability Statements

All the data available upon the request

Credit authorship contribution statement

Altaf Hussain Solangi: Conceptualization and Methodology. Saeed Khan Lakho: Literature review and Fabrication. Wajid Ali Jatoi: Analysis and Writing. Shahnaz Memon: Collecting the data, Administration, and Drafting. Syed Qutaba: Conceptualization, Methodology, Writing and Citation.

Compliance with ethical standards

Declaration : The authors declare to have no known competing financial interests.

Ethical issues: None

Consent of participate: Not applicable

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