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Research Article

Assessment of heterosis and combining ability for yield and oil traits in cotton (*Gossypium hirsutum* L.) contributing to the revival of India's cotton sector

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Abstract
Cotton is a major commercial crop with global importance, especially in the textile sector. Enhancing its yield and fibre quality through hybrid breeding is a key goal in crop improvement. This study was conducted during *Kharif* 2024 at Lovely Professional University, School of Agriculture, Genetics and Plant Breeding Research Farm in Phagwara, Punjab, to evaluate combining ability, gene action, and heterosis in cotton (*Gossypium hirsutum* L.). A total of 24 F_1 hybrids were developed using 10 cotton genotypes (6 lines and 4 testers) along with a standard check (G. Cot. Hy 18) in a line × tester design. Analysis of variance revealed significant variability in seed yield, boll weight, and fibre quality traits, indicating potential for improvement. Non-additive gene action was observed for seed yield, boll production, and fiber quality, whereas additive gene action was prominent for earliness traits like flowering and boll bursting. The lines 761H20 and GJHV-510, along with the tester Sanjay (CJ-73), were identified as effective general combiners for seed yield, boll weight, and fiber quality. Among the hybrids, 761H20 × V-797, GJHV-503 × Guj. Cot.-15, and 761H20 × Deviraj stood out as the top performers, exhibiting strong performance, high SCA effects, and improved heterosis for yield and fiber traits. Additionally, the hybrid GJC-101 × V-797 showed excellent performance in boll production and weight. These hybrids have strong potential for commercial through heterosis breeding.. The variance ratio (σ^2GCA/σ^2SCA) being less than one confirmed the predominance of non-additive gene action. This study provides insights for developing superior cotton hybrids.

Keywords: Combining ability, Cotton, Earliness, Gene action, Heterosis, Hybridization, Yield

INTRODUCTION

Cotton, a crucial cash crop, has over 50 species in the genus *Gossypium,* of which at least 45 are categorized as diploid (2n = 2x = 26 chromosomes) and at least 6 are Allotetraploid (2n = 4x = 52 chromosomes) (Amna *et al*., 2023). Cotton is a vital cash crop, accounting for approximately 21% of global fibre production. Often referred to as the "King of Fiber" and "White Gold," it encompasses several cultivated species, including *Gossypium arboreum*, *Gossypium herbaceum*, *Gossypium hirsutum*, and *Gossypium barbadense* (Malathi *et al*., 2019). Cotton is primarily cultivated for its fiber, which accounts for 34-48% of its total weight. This fiber is used in natural textiles, while the oil extracted from cotton is utilized in food products for humans, accounting for 18-26% of the cotton's weight (Venkatesan *et al*., 2024). Additionally, the by-product meal is a protein-rich animal feed. Any surplus production can be exported for foreign currency.

Most cotton breeding programs focus on enhancing the quantity and quality of the fibers, promoting early maturity, and improving resistance to pests and diseases (Shahzad *et al*., 2022). Given the global interest in cotton, research centers are dedicated to developing unique cultivars by studying variations and genetic traits that may help achieve these goals. In the 2021-22 period, India's cotton productivity was approximately 445 kg ha^{-1}, positioning the country as one of the leading cotton producers, consumers, and exporters globally (Directorate of Economics and Statistics, 2022-23). India ranks first globally in cotton acreage, with approximately 11.91 million hectares dedicated to cotton cultivation, accounting for about 36% of the total world area of 32.636 million hectares. Furthermore, India is the third-largest exporter, holding a 4.6% share in the textile industry.

Utilizing heterotic potential (heterosis) in cotton has been recoginsed as a benefical approach for enhancing yield and other key traits in breeding programs. The primary objective of heterosis breeding is to achieve a substantial improvement in crop yield and quality (Rakesh *et al*., 2024). With this perspective in mind, the current study aims to examine the extent and direction of standard heterosis for yield and its contributing characteristics in cotton. To determine which lines, have the best combining effects, it is necessary to evaluate the general combining ability (GCA) in parents and the specialized combining ability (SCA) in crosses, as stated by Solangi *et al*., (2025). The GCA provides insights into the additive gene effects, while the SCA reveals both intra-allelic as well as inter-allelic interactions for (dominance) and (epistasis) respectively Bilwal *et al*., (2018).

SCA is the performance of a cross that deviates from expectations based on the parents GCA. The Line x Tester analysis technique is one of the most widely used and methodical methods for determining superior parents and crosses proposed by Kempthorne (1957). The present study aimed to estimate heterosis and combining ability in cotton (*Gossypium hirsutum* L.) for 12 traits, including yield and its contributing components, using a line × tester mating scheme.

MATERIALS AND METHODS

The present research study was carried out at Lovely Professional University, School of Agriculture, Genetics and Plant Breeding Research Farm, Phagwara, Punjab, through the development 24 F_1s using 10 genotypes of upland cotton (*G. hirsutum* L.) (6 lines and 4 testers) and one standard check (G. Cot. Hy 18) (Table 1) evaluated in RBD with 3 replications in *Kharif* 2024. Twelve quantitative traits were examined from five randomly selected plants of each parent and F_1 generation *viz.* DFF- Days to 50% flowering, DBB- Days to 50% boll bursting, PH- Plant height (cm), NPP- Number of monopodia per plant, SPP- Number of sympodia per plant, BPP- Number of bolls per plant, BW- Boll weight (g), SYP- Seed cotton yield per plant (g), GP- Ginning percentage (%), SI- Seed index (g), LI- Lint index and OC-Oil content (%).

Estimation of heterosis

Analysis of variance (ANOVA) was used to determine the significance of treatment differences
using the procedure outlined by Panse and Sukhatme (1985) for Randomized Block Design (RBD) to all the biometric (quantitative) traits studied. The performance of the F_1 hybrid was evaluated based on the heterosis over standard check, following the method proposed by Fonseca and Patterson (1968). The Percentage Increase or decrease in F_1 hybrids over standard checks was calcualated to determine heterotic potential (heterosis) in both positive and negative directions, using the formulae given by Singh and Chaudhary (1977).

Heterosis over standard check (SH)

$$SH\% = \frac{F1 - SC}{SC} \text{ x } 100 \quad \text{Eq.1}$$

Where, SH = Standard or commercial check mean performance,

F1 = Mean performance of the F hybrid

SC = Mean performance of the Standard Check variety or hybrids.

Estimation of General Combining Ability (GCA) and Specific Combining Ability (SCA)

ANOVA for the analysis of combining ability using the Line x Tester method and a test of significance for different genotypes was performed according to Kempthorne (1957) and Singh and Chaudhary (1985). By analyzing the two-way table of male and female parents and then totaling up the results across several replications, the individual effects of GCA and SCA were estimated.

(a) GCA effects of A^{th} line

$$Gi = \frac{xA}{Tr} - \frac{\sum x}{LTr} \quad \text{Eq.2}$$

Where,

G_i = General Combining Ability (GCA) effect of the *i-th* parent (line or tester)

xA = Total performance (sum of trait values) of all crosses involving the *i-th* parent

Tr = Number of testers (if the parent is a line) or number of lines (if the parent is a tester)

∑x = Total performance (sum of all trait values) for all hybrids in the experiment

L = Number of lines in the line × tester design

Tr = Number of testers (appears again as part of total number of hybrids: L × Tr)

(b) GCA effects of B^{th} tester

$$Gj = \frac{xB}{Lr} - \frac{\sum x}{LTr}$$ Eq. 3

Where,

G_j = General Combining Ability (GCA) effect of the *j-th tester*

xB = Total performance (sum of trait values) of all crosses involving the *j-th tester*

Lr = Number of lines crossed with the *j-th tester* (in most line × tester designs, Lr = number of lines = L)

∑x = Total performance (sum of all trait values) for all hybrids in the experiment

L = Number of lines

Tr = Number of testers

L × Tr = Total number of hybrids evaluated

(c) SCA effects of AB^{th} cross

$$Sij = \frac{xAB}{r} - \frac{xA}{T} - \frac{xB}{Lr} + \frac{\sum x.}{LTr}$$ Eq.4

Where,

$\sum x$. = total sum of all crosses, *xA.* = total sum of A^{th} lines over all testers and replications

x_A = total of B^{th} tester over all lines and replications,

x_{AB} = AB^{th} line x tester combination total over all replications,

r = No. of replications, *L and T* = No. of of lines and testers.

Estimation of variances of GCA and SCA

Estimation of variance of GCA and SCA was calculated by formulae (Singh and Chaudhary, 1977)

$$\sigma^2 GCA = \frac{(M.L+M.T-2.M.L.T)}{r(L+T)}$$ Eq.5

$$\sigma^2 SCA = \frac{(M.L.T - M.r)}{r(L+T)}$$ Eq.6

Where,

$\sigma 2GCA$

M.L = Mean squares of female lines, M.T = Mean squares of male testers, M.L.T = Mean squares of line x tester (cross), L *and* T = number of lines and testers, r = number of replications.

Contribution of line, testers and their interactions to total variance

Line, testers, and their interactions proportional contributions to estimate total variance
as per (Singh and Chaudhary, 1977)

$$Contribution\ of\ Line = \frac{S.S.(L)}{S.S\ (Crosses)} \times 100$$ Eq.7

$$Contribution\ of\ Tester = \frac{S.S.(T)}{S.S\ (Crosses)} \times 100$$ Eq.8

$$Contribution\ of\ Line\ x\ Tester = \frac{S.S\ (L\ x\ T)}{S.S\ (Crosses)} \times 100$$ Eq.9

Where,

S.S.L = sum squares of lines

S.S.T = sum squares of testers

S.S. crosses = sum squares of crosses

S.S Line x Tester = sum squares of line × tester

RESULTS AND DISCUSSION

Analysis of Variance

The results showed highly significant differences ($p < 0.01$) for all traits (days to 50% flowering, days to 50% boll bursting, plant height (cm), number of monopodia per plant, number of sympodia per plant, number of bolls per plant, boll weight (g), seed cotton yield per plant (g), ginning percentage (%), seed index (g), lint index (g), oil content (%) among genotypes, demonstrating the presence of genetic variability among the studied lines and hybrids (Table 2). The ANOVA results revealed significant genetic variation for most traits, highlighting the potential for genetic improvement through hybridization. The significant Line × Tester interaction effects suggest a strong role of specific parental combinations in determining hybrid performance (Table 3). These findings emphasize the importance of selecting superior parents and utilizing heterosis to enhance cotton yield and its associated traits. Patel *et*

Table 1. Parents used in the crossing programme with a commercial check

Lines (6)	Testers (4)	Commercial Check
Guj. Cot. - 23 GJHV- 503 761H20 GJC- 101 GJHV- 510 GJHV- 517	Deviraj V-797 Sanjay (CJ-73) Guj. Cot. -15	G. Cot. Hy 18

Table 2. ANOVA for Randomized Block Design in cotton for 12 traits

Source of Variation	Df	DFF	DBB	PH	MPP	SPP	BPP
Replication	2	1.54	6.56	9.41	0.20	0.16	6.06
Genotypes	33	80.55**	213.72**	1226.83**	1.52**	53.39**	84.88**
Error	66	1.60	9.90	23.07	0.08	2.79	17.09
Source of Variation	**Df**	**BW**	**SYP**	**GP**	**SI**	**LI**	**OC**
Replication	2	0.11	883.17	2.57	1.28	0.70	0.63
Genotypes	33	2.04**	7858.10**	29.74**	4.90**	3.20**	3.30**
Error	66	0.11	604.92	3.87	0.67	0.24	0.23

*, ** denotes significance at 5% and 1% respectively

al. (2024), Faldu *et al*., (2024), and Hussain *et al*., (2023) reported similar patterns of genetic variability among parental lines and F_1 hybrids in upland cotton (*G. hirstum* L.), based on line x tester analysis for traits such as seed cotton yield, boll weight, ginning percentage and lint index in cotton.

Heterosis for earliness and yield-related traits

The present study revealed significant heterosis for earliness traits, growth parameters, yield components, and fiber quality traits, emphasizing the potential of specific crosses in improving cotton performance (Table 4). For earliness traits, crosses 761H20 x V-797, 761H20 x Deviraj, and 761H20 x Sanjay (CJ-73) indicate their suitability for developing early-maturing cotton varieties. Similarly 761H20 x V-797, 761H20 x Guj. Cot. -15, and Guj. Cot. – 23 x Guj. Cot.- 15 demonstrated early boll bursting (DBB), which is advantageous for synchronized harvesting and reduced environmental stress exposure. These findings align with the reports of Patel *et al*. (2024), Faldu *et al.* (2024), and Madugula *et al.* (2023), who observed significant heterosis for earliness traits in *G. hirsutum* hybrids.

Regarding growth parameters, the present study recorded enhanced plant height (PH) in hybrids GJC-101 x V-797, GJHV-510 x Deviraj, and GJHV-510 x Sanjay (CJ-73). However, moderate plant height is generally preferred for mechanized harvesting. For monopodia per plant (MPP) and sympodia per plant (SPP), the highest heterosis was observed in GJHV-510 x V-797 and GJHV-510 x Sanjay (CJ-73), indicating their potential for breeding ideal canopy structures and yield efficiencies. Similar patterns in growth traits were reported in cotton, particularly for traits such as plant height and the number of sympodial per plant, as noted by Keerthivarman *et al.* (2022), Vanapariya *et al.* (2024), and Richika *et al. (*2021), which support the current findings.

In terms of yield components and fiber traits, boll weight (BW) showed highest heterosis in GJHV-510 × Deviraj, 761H20 × Sanjay (CJ-73), and GJC-101 × V-797. The hybrids 761H20 × Sanjay (CJ-73), 761H20 × Deviraj, and GJHV-510 × Sanjay (CJ-73) recorded maximum heterosis for seed cotton yield per plant (SYP), indicating strong commercial potential. These results are in agreement with Patel *et al*., (2024) and Madugula *et al*., (2023), who reported significant heterosis for yield-related traits in cotton.

For fiber quality, ginning percentage (GP) was highest in GJHV-517 × Deviraj, GJHV-503 × Deviraj, and GJHV -510 × Deviraj, indicating their efficiency in fiber recovery. The seed index (SI) and lint index (LI) were notably improved in GJHV-517 × Sanjay (CJ-73) and GJHV-517 × Deviraj, respectively. Moreover, increased oil content (OC) was observed in GJHV-510 × Guj. Cot.-15, GJHV-503 × V-797, and 761H20 × Deviraj, showing their potential in dual-purpose breeding for fiber and oil. These findings are consistent with those of Richika *et al*. (2021), who found fibrous quality as well as oil content, and others who reported similar improvements in oil and fibre traits. The present study highlights the genetic variability and heterotic potential of specific hybrids across agronomic and quality traits. These superior crosses offer valuable resources for hybrid development in cotton breeding programs aiming at enhanced productivity, fiber quality, and adaptability. The best-performing hybrids for better parent heterosis (BPH) and standard heterosis (SH) are detailed in Table 5.

Combing ability for earliness and yield related traits General Combining Ability (GCA) effects in cotton hybrids

The present study revealed significant general combining ability (GCA) effects among the parental lines, highlighting promising combiners for key agronomic and economic traits in cotton breeding (Table 6). For earliness traits, GJHV-517 and GJC-101 among females, and Guj. Cot. - 15 among testers, exhibited the most desirable negative GCA effects for days to 50% flowering (DFF), indicating their suitability for breeding early-

Table 3. Analysis of variance for Line X Tester involving parents for yield and its attributing traits

Source of Variation	Df	DFF	DBB	PH	MPP	SPP	BPP
Replication	2	2.54	22.10	6.46	0.22	2.60	10.31
Genotypes	33	80.55**	231.72**	1226.83**	1.52**	53.39**	84.88**
Crosses	23	93.52 **	222.14 **	879.94 **	1.79 **	37.86 **	94.18 **
Line (c)	5	285.89**	512.18 **	1673.65 *	2.68	114.03**	150.24
Tester (c)	3	118.13 *	296.38	1828.25 *	3.15	48.25 *	180.97
L x T (c)	15	24.47 **	110.62 **	425.72 **	1.23 **	10.39 **	58.13 **
Parent	9	42.53**	111.80**	1788.13**	0.51**	55.50**	52.38**
Error	46	1.76	7.18	23.19	0.10	3.17	12.51
Total	**136**						
Source of Variation	Df	BW	SYP	GP	SI	LI	OC
Replication	2	0.27	181.52	4.74	0.35	0.31	0.16
Genotypes	33	2.04**	7858.09**	29.73**	4.90**	3.20**	3.30**
Crosses	23	2.39 **	6862.15 **	33.57 **	4.11 **	3.38 **	4.07 **
Line(c)	5	3.39	12617.19 *	14.81	5.00	5.27 *	5.88
Tester(c)	3	5.96 *	15233.68 *	160.40 **	8.76	11.07 **	5.40
L x T (c)	15	1.34 **	3269.50 **	14.46 **	2.88 **	1.21 **	3.20 **
Parent	9	0.59**	7025.07**	5.36	4.58**	1.08**	1.36**
Error	46	0.10	286.20	4.32	0.46	0.27	0.25
Total	**136**						

*, ** denotes significance at 5% and 1% respectively

maturing varieties. Guj. Cot. -15 was the best tester for early boll bursting, while 761H20 and GJHV=510 demonstrated the least desirable GCA effects for days to 50% boll bursting (DBB), similar to the observations by Singh *et al*. (2024).

For growth traits, GJHV-510 and GJC-101 were the best combiners for plant height (PH), whereas 761H20 and Guj. Cot.-23 contributed to reduced plant height. Among testers, Sanjay (CJ-73) and V-797 showed positive GCA effects, favoring tall plants, while Deviraj and Guj. Cot. - 15 contributed to reduced height. For monopodia per plant (NPP), GJHV-503 and GJHV-510, and Sanjay (CJ-73), emerged as the best combiners for increased monopodial branches. In sympodia per plant (SPP), GJHV-510 and GJC-101 recorded the highest positive GCA effects, with Guj. Cot. - 15 being the best tester.

For yield components, 761H20 and GJHV-517 were the best general combiners for bolls per plant (BPP), while GJHV-510 and Guj.Cot. -23 exhibited the highest positive GCA effects for boll weight (BW). Among testers, Sanjay (CJ-73) and Deviraj made a significant contribution to increased boll weight. The most promising combiners for seed cotton yield per plant (SYP) were 761H20 and GJHV-510 among females, and Sanjay (CJ–73) and V-797 among testers, confirming their suitability for high-yield breeding programs.

In fiber and seed traits, GJHV-517 and Guj. Cot. - 23 exhibited the highest GCA effects for ginning percentage (GP), while Deviraj and Guj. Cot. - 15 were the best testers for this trait. GJHV-517 and Guj. Cot. - 23 also contributed positively to the seed index (SI), whereas GJC-101 and GJHV-517 were favourable for lint index (LI). Deviraj was the most effective tester for improving lint yield. Regarding oil content (OC), GJHV-503 and Guj. Cot. - 23 among females, and Guj. Cot. - 15 among testers were the best general combiners for enhancing oil percentage in seeds.

Based on their superior GCA effects across multiple traits, the top three general combiners identified were: 761H20 – Strongest contributor to seed cotton yield and boll production. GJHV-510 – Best performer for plant height, boll weight, and seed cotton yield. Sanjay (CJ-73) – Most promising tester for plant height, boll weight, and seed cotton yield. These combiners hold significant potential for hybrid development aimed at improving cotton yield, earliness, and fiber quality. The findings are in line with those of Vanapariya *et al*. (2024) and Richika *et al*. (2021), who also reported a strong GCA effect for oil content and yield-related traits in cotton.

Specific Combining Ability (SCA) effects in cotton hybrids

The present study revealed that the specific combining ability (SCA) effects indicated significant genetic interactions among hybrids, identifying superior cross-combinations for key agronomic and economic traits in cotton breeding (Table 7). For earliness traits, hybrids Guj. Cot. - 23 × Guj. Cot. - 15, 761H20 × V=797, and GJHV-510 × Guj. Cot. - 15 exhibited the most desirable negative SCA effects for days to 50% flowering (DFF), making them promising for early-maturing varieties. The present study found that Guj. Cot. - 23 × Guj. Cot. - 15 and 761H20 × V-797 showed the greatest negative SCA effects for days to 50% boll bursting (DBB), indi-

Table 4. Heterobeltiosis and Standard Heterosis for 12 traits in cotton

Cross No.	Genotypes	DFF		DBB		PH		MPP		SPP		BPP	
		BPH	SH	BPH	SH	BPH	SH	BPH	SH	BPH	SH	BPH	SH
C1	Guj.Cot. - 23 x Deviraj	1.04	-1.52	0.29	5.59*	-16.96**	-18.47**	16.26**	17.21**	-10.99	-7.6	-5.09	-5.54
C2	Guj. Cot. -23 x V-797	7.65**	-0.51	-0.3	4.66	27.39**	-19.13**	-32.45**	-16.39**	16.34**	-13.16*	-7.27	-2.95
C3	Guj. Cot. - 23 x Sanjay (CJ-73)	10.00**	-5.56**	5.14*	1.55	12.64**	-13.60**	30.89**	31.97**	-7.85	2.92	-28.81**	-9.8
C4	Guj. Cot. - 23 x Guj. Cot. – 15	-9.34**	-16.67**	-7.17**	-11.49**	10.29**	-16.12**	-6.94	9.84	4.85	20.18**	3.01	15.94*
C5	GJHV-503 x Deviraj	1.61	-4.55**	-3.35	-1.55	-2.59	-15.96**	25.20**	26.23**	-10.46*	7.6	-9	-9.43
C6	GJHV-503 x V-797	8.74**	0.51	5.49*	7.45**	49.20**	-5.29**	11.26*	37.70**	-14.60**	2.63	-8.29	-4.02
C7	GJHV-503 x Sanjay (CJ-73)	17.06**	0.51	10.29**	6.52**	34.64**	3.27	42.62**	42.62**	-11.19*	6.73	-6.66	18.26*
C8	GJHV-503 x Guj. Cot. -15	-7.69**	-15.15**	-4.89	-9.32**	11.36**	-15.30**	11.81*	31.97**	2.19	22.81**	4.39	17.50*
C9	761H20 x Deviraj	-4.14*	-18.18**	-11.86**	-14.60**	-10.24**	-18.36**	-15.45**	-14.75*	-2.86	-0.58	10.2	15.80*
C10	761H20 x V-797	-6.51**	-20.20**	-16.99**	-19.57**	28.68**	-18.32**	-31.13**	-14.75*	3.1	-2.63	13.4	19.16*
C11	761H20 x Sanjay (CJ-73)	-1.18	-15.66**	-11.90**	-14.91**	8.54**	-16.75**	24.59**	24.59**	-1.05	10.53	2.6	30.00**
C12	761H20 x Guj. Cot. – 15	-2.37	-16.67**	-4.89	-9.32**	10.70**	-15.80**	-4.17	13.11*	7.14	22.81**	8.56	22.19**
C13	GJC-101 x Deviraj	-5.33**	-19.19**	11.88**	5.28*	-2.51	-15.17**	21.14**	22.13**	6.63	17.54**	-0.33	-0.8
C14	GJC-101 x V-797	-5.92**	-19.70**	0.99	-4.97*	61.74**	2.67	-17.88**	1.64	7.43	18.42**	24.14**	29.92**
C15	GJC-101 x Sanjay (CJ-73)	-4.73*	-18.69**	4.62	-1.55	32.69**	1.78	31.97**	31.97**	25.39**	40.06**	-20.71**	0.47
C16	GJC-101 x Guj. Cot. – 15	-7.69**	-21.21**	-5.94*	-11.49**	10.69**	-15.81**	-9.72*	6.56	5.87	21.35**	7.13	20.58*
C17	GJHV-510 x Deviraj	18.79**	-1.01	-7.42**	-10.87**	14.05**	-13.29**	-16.28**	-11.48*	36.86**	40.06**	8.17	7.66
C18	GJHV-510 x V-797	11.52**	-7.07**	-10.65**	-13.98**	60.95**	2.17	21.19**	50.00**	81.15**	37.72**	-8.97	-4.73
C19	GJHV-510xSanjay (CJ-73)	18.18**	-1.52	-5.16*	-8.70**	40.53**	6.84**	35.66**	43.44**	28.80**	43.86**	-26.93**	-7.42
C20	GJHV-510 x Guj. Cot. – 15	-1.82	-18.18**	-4.56	-9.01**	18.60**	-9.83**	5.56	24.59**	14.80**	31.58**	9.39	23.13**
C21	GJHV-517 x Deviraj	-19.17**	-21.21**	-2.36	2.8	24.34**	-8.11**	-6.67	14.75*	7.71	10.23	9.67	9.16
C22	GJHV - 517 x V-797	-15.30**	-21.72**	-8.58**	-4.04	41.48**	-10.19**	-4.64	18.03**	50.97**	14.33*	18.99*	24.53**
C23	GJHV-517 x Sanjay (CJ-73)	-2.94	-16.67**	-0.96	-4.35	18.04**	-12.76**	-2.67	19.67**	2.62	14.62*	-13.73*	9.3
C24	GJHV-517 x Guj. Cot. - 15	-14.84**	-21.72**	-10.10**	-14.29**	18.08**	-12.73**	7.33	31.97**	13.14*	29.68**	8.18	21.76**

*, ** denotes significance at 5% and 1% respectively.

Table 4. Heterobeltiosis and Standard Heterosis for 12traits in cotton **(Contd…..)**

Cross No.	Genotypes	BW		SYP		GP		SI		LI		OC	
		BPH	SH	BPH	SH	BPH	SH	BPH	SH	BPH	SH	BPH	SH
C1	Guj.Cot. - 23 x Deviraj	-1.78	23.89**	-1.94	-19.32*	13.32**	17.10**	0.61	18.47**	28.66**	33.90**	6.16**	12.09**
C2	Guj. Cot. -23 x V-797	1.07	27.49**	5.48	16.41*	10.78*	16.10**	-2.76	21.40**	-7.65	9.38	5.36**	11.25**
C3	Guj. Cot. - 23 x Sanjay (CJ-73)	6.22	33.97**	-13.38	-4.46	7.55	16.38**	15.74*	19.16**	1.08	4.03	4.11*	10.44**
C4	Guj. Cot. - 23 x Guj. Cot. – 15	-2.31	23.22**	-27.25**	-13.28	13.43**	17.22**	17.74**	18.51**	18.52**	9.16	0.49	8.86**
C5	GJHV-503 x Deviraj	13.97*	13.81*	-17.82*	-19.06*	19.83**	20.00**	-13.06*	9.81	26.38**	32.74**	3.58	15.93**
C6	GJHV-503 x V-797	-11.13*	-4.87	3.26	13.95	1.25	6.1	-8.89	15.06*	-5.55	11.87	-0.95	10.86**
C7	GJHV-503 x Sanjay (CJ-73)	27.34**	26.99**	9.61	20.89**	-3.33	4.61	2.83	29.87**	-3.53	1.32	-4.06*	7.38**
C8	GJHV-503 x Guj. Cot. -15	17.45**	26.67**	-0.23	18.93*	15.18**	18.10**	-10.39*	13.18*	1.46	6.57	-2.5	9.12**
C9	761H20 x Deviraj	10.44	10.29	42.05**	33.59**	14.39**	21.90**	3.64	22.05**	32.63**	38.04**	-1.42	5.49*
C10	761H20 x V-797	-28.71**	-23.70**	9.26	20.58**	-4.8	1.46	-27.80**	-9.87	-30.55**	-17.75**	4.12*	11.43**
C11	761H20 x Sanjay (CJ-73)	29.18**	28.83**	25.62**	38.55**	-10.52*	-3.17	26.14**	29.87**	-7.98	-5.3	-2.4	4.45*
C12	761H20 x Guj. Cot. – 15	-8.03	-0.81	10.13	31.27**	9.03*	16.19**	-5.35	-4.74	2.04	-4.4	1.94	10.44**
C13	GJC-101 x Deviraj	12.85*	21.26**	-5.4	-2.98	13.06**	21.90**	-9.07	7.08	23.95**	33.80**	-5.11*	1.41
C14	GJC-101 x V-797	6.93	14.89**	22.60**	35.30**	-4.8	2.65	-16.62**	4.09	7.6	27.44**	-5.95**	0.51
C15	GJC-101 x Sanjay (CJ-73)	17.82**	26.59**	16.67*	28.68**	-0.73	7.42	15.32*	26.62**	23.95**	33.80**	-11.00**	-4.89*
C16	GJC-101 x Guj. Cot. – 15	-26.62**	-20.85**	-23.97**	-9.37	6.88	15.24**	18.27**	29.87**	20.02**	29.56**	2.06	10.57**
C17	GJHV-510 x Deviraj	36.02**	38.05**	41.50**	24.55**	17.30**	22.86**	-10.26	5.68	17.36**	22.14**	-6.22**	0.44
C18	GJHV-510 x V-797	22.77**	31.41**	17.53*	29.71**	-19.14**	-15.26**	-5.85	17.53**	-31.40**	-18.75**	6.72**	14.30**
C19	GJHV-510xSanjay (CJ-73)	34.30**	36.30**	21.12**	33.59**	-1.5	6.59	23.97**	27.63**	15.55*	18.91**	3.2	10.53**
C20	GJHV-510 x Guj. Cot. – 15	9.04	17.60**	-10.71	6.44	13.67**	19.05**	12.77*	13.51*	13.80*	4.82	8.37**	17.40**
C21	GJHV-517 x Deviraj	17.53**	20.72**	-22.82**	-14.49	15.28**	24.30**	8.3	27.53**	34.20**	39.68**	-1.44	0.24
C22	GJHV - 517 x V-797	-27.32**	-22.21**	9.48	21.31**	1.3	9.23*	1.43	26.62**	0.49	19.02**	-7.25**	-6.28**
C23	GJHV-517 x Sanjay (CJ-73)	22.60**	25.92**	9.03	20.80**	-0.84	7.3	28.99**	33.77**	15.20*	19.23**	0.09	6.17**
C24	GJHV-517 x Guj. Cot. - 15	2.26	10.29	-4.7	13.6	8.64*	17.14**	22.42**	26.95**	11.62	15.52*	7.35**	16.30**

*, ** denotes significance at 5% and 1% respectively.

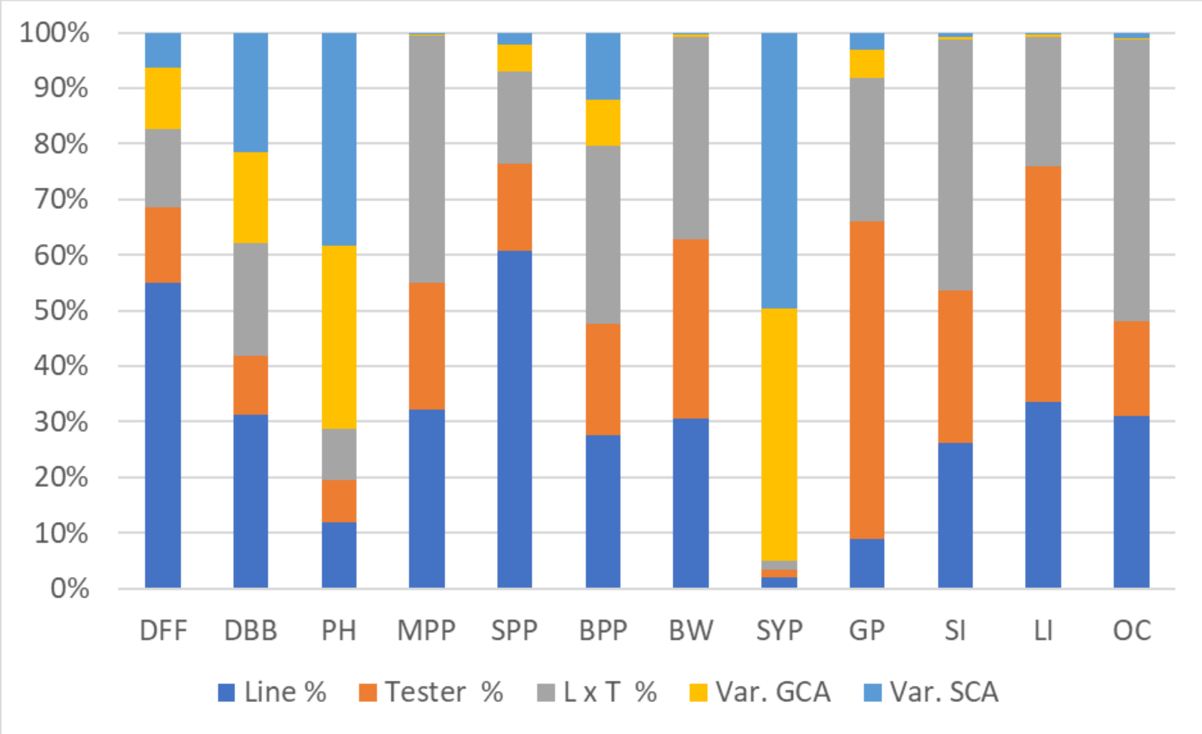

Fig. 1. *Contribution of Lines, Testers and Line X Tester for gene action*

acting early boll maturity. In contrast, 761H20 × Guj. Cot. - 15 and GJHV-510 × Guj. Cot. - 15 demonstrated delayed maturity. Similar trends were reported in upland cotton (*G. hirsutum*) for traits such as seed cotton yield, boll weight and oil content by Zhang *et al*., (2024).

In growth traits, GJHV-517 × Deviraj and GJHV-503 × Sanjay (CJ-73) recorded the highest positive SCA effects for plant height (PH), indicating their potential for taller plants, whereas GJHV-517 × Sanjay (CJ-73) and GJC-101 × Guj. Cot. - 15 were ideal for shorter stature. For monopodia per plant (NPP), hybrids GJHV-510 × V -797 and Guj. Cot. - 23 × Deviraj showed the highest positive SCA effects, favoring monopodial branch development. The present study observed significant positive SCA effects for sympodia per plant (SPP), in the hybrids GJC-101 × Sanjay (CJ-73) and Guj. Cot. - 23 × Guj. Cot. – 15 suggesting their potential for improved fruiting branches. Similar findings were reported by Bhimireddy *et al*. (2023) in upland cotton (*Gossypium hirsutum*) for traits such as seed cotton yield, plant height, and number of bolls per plant.

For yield components, hybrids GJHV-503 × Sanjay (CJ-73) and GJC-101 × V-797 exhibited the most positive SCA effects for bolls per plant (BPP), whereas GJHV-503 × V-797 and GJHV-510 × V-797 recorded negative effects. The highest positive SCA effects for boll weight (BW) were observed in GJC-101 × V-797 and 761H20 × V-797, while GJHV-517 × V-797 and GJHV-510 × Guj. Cot. - 15 showed negative effects Rao *et al*. (2024). The most promising hybrids for seed cotton yield per plant (SYP) were GJHV-503 × Guj.Cot. - 15 and 761H20 × Deviraj, whereas 761H20 × V-797 and GJHV-503 × Deviraj exhibited significantly negative effects.

The present study revealed that the hybrids *Guj. Cot.-23 × V-797* and *GJHV-510 × Deviraj* exhibited the highest specific combining ability (SCA) effects for ginning percentage (GP), indicating their potential for improved fiber recovery. In contrast, *GJHV-510 × V-797* and *761H20 × Sanjay (CJ-73)* showed negative SCA effects for this trait. For seed index (SI), *761H20 × Deviraj* and *GJHV-517 × Guj. Cot.-15* were identified as the most effective combiners, contributing positively to seed weight, while *761H20 × V-797* and *761H20 × Guj. Cot.-15* showed negative SCA effects. These results are in agreement with the findings of Rakesh *et al*., (2016), who also reported variability in SCA effects for fiber and seed traits in *Gossypium hirsutum* hybrids. The present study recorded significant positive SCA effects for lint index (LI) in the hybrids 761H20 × Deviraj and Guj. Cot. - 23 × V-797, while 791H20 × V-797 and GJC-101 × Deviraj showed negative effects. Similar trends were observed by Ali *et al*. (2024) in their evaluation of upland cotton hybrids. In oil content (OC), GJHV-517 × V-797 and GJHV-517 × Guj. Cot. - 15 recorded the highest SCA effects, while GJHV-510 × Deviraj and Guj. Cot. - 23 × Guj. Cot. - 15 showed negative effects.

Top specific combiners

Based on their superior SCA effects across multiple traits (Table 7), the top three specific combiners identi-

Table 5. Best-performing hybrids for heterosis in both better parent (BPH) and standard (SH)

S. No	Characters	Best Cross for BPH	BPH (%)	Best Cross for SH	SH (%)
1	Days to 50% Flowering	Guj. Cot. - 23 × Guj. Cot. – 15	-6.24**	761H20 × V-797	-5.30**
2	Days to 50% Boll Bursting	761H20 × V-797	-9.30**	GJHV-510 × Guj. Cot. -15	-7.50**
3	Plant Height (cm)	GJHV-517 × Deviraj	18.45**	GJHV-503 × Sanjay (CJ-73)	16.89**
4	Number of Monopodia per Plant	GJHV-510 × V-797	2.12**	GJC-101 × Sanjay (CJ-73)	1.98**
5	Number of Sympodia per Plant	GJC-101 × Sanjay (CJ-73)	5.89**	Guj. Cot. - 23 × Guj. Cot. - 15	5.42**
6	Number of Bolls per Plant	GJHV-503 × Sanjay (CJ-73)	12.65**	GJC-101 × V-797	11.98**
7	Boll Weight (g)	GJC-101 × V-797	6.84**	761H20 × V-797	5.95**
8	Seed Cotton Yield per Plant (g)	GJHV-503 × Guj. Cot. – 15	45.75**	761H20 × Deviraj	42.89**
9	Ginning Percentage (%)	Guj. Cot. - 23 × V-797	3.95**	GJHV-510 × Deviraj	3.72**
10	Seed Index (g)	761H20 × Deviraj	4.50**	GJHV-517 × Guj. Cot. - 15	4.12**
11	Lint Index	761H20 × Deviraj	2.89**	Guj. Cot. - 23 × V- 797	2.53**
12	Oil Content (%)				

Table 6. GCA effect for 12 traits among parents in Cotton

S. No.	Genotypes	DFF	DBB	PH	MPP	SPP	BPP	BW	SYP	GP	SI	LI	OC
LINES													
1	Guj. Cot. – 23	4.29**	5.90 **	-13.23 **	-0.32 **	-3.59 **	-4.53 **	0.54 **	-48.28 **	1.61 *	0.15	-0.07	0.54 **
2	GJHV-503	5.21**	6.65 **	4.82 **	0.66 **	-1.45 **	-1.89	-0.02	-12.57 *	0.04	-0.09	-0.13	0.57 **
3	761H20	-3.37**	-9.85 **	-14.24 **	-0.67 **	-2.00 **	5.02 **	-0.61 **	45.020 **	-1.05	-0.88 **	-0.79 **	0.05
4	GJC-101	-4.71**	2.403 **	8.40 **	-0.12	1.83 **	1.07	-0.27 **	-1.66	-0.1	-0.1	1.00 **	-1.05 **
5	GJHV-510	3.71**	-5.60 **	14.10 **	0.33 **	5.01 **	-2.29 *	0.73 **	25.86 **	-1.33 *	-0.19	-0.53 **	0.54 **
6	GJHV-517	-5.12**	0.49	-0.75	0.11	0.2	2.63 *	-0.37 **	-8.37	0.84	1.11 **	0.51 **	-0.65 **
TESTERS													
7	Deviraj	1.07 **	3.43 **	-9.12 **	-0.38 **	-1.16 **	-3.08 **	0.26 **	-33.97 **	3.24 **	-0.29 *	1.14 **	-0.32 **
8	V-797	0.74 **	0.37	5.47 **	-0.23 **	-1.54 **	0.12	-0.60 **	24.06 **	-3.05 **	-0.56 **	-0.63 **	-0.12
9	Sanjay (CJ-73)	1.99 **	1.99 **	11.44 **	0.57 **	0.79 *	-1.38	0.67 **	24.41 **	-1.95 **	1.02 **	-0.20	-0.36 **
10	Guj. Cot. – 15	-3.76 **	-5.79 **	-7.79 **	0.05	1.92 **	4.33 **	-0.33 **	-14.50 **	1.77 **	-0.17	-0.31 **	0.81 **
SE± (Lines)		0.38	0.77	1.39	0.09	0.51	1.02	0.09	4.88	0.60	0.20	0.15	0.14
CD @ 5% (Lines)		0.77	1.56	2.80	0.19	1.03	2.06	0.18	9.83	1.21	0.39	0.30	0.29
CD @ 1% (Lines)		1.03	2.08	3.74	0.25	1.38	2.74	0.24	13.12	1.61	0.53	0.40	0.39

*, ** denotes significance at 5% and 1% respectively.

Table 7. SCA effect for 12 traits among hybrids in cotton

S. No	Genotypes	DFF	DBB	PH	MPP	SPP	BPP	BW	SYP	GP	SI	LI	OC
1	Guj.Cot. - 23 x Deviraj	1.93*	2.49	5.64*	0.65**	-0.70	0.97	-0.42*	-2.54	-3.09*	0.19	0.10	0.58*
2	Guj. Cot. -23 x V-797	2.93**	4.54**	-10.36**	-0.87**	-1.59	-1.13	0.62**	31.59**	2.84*	0.76	0.33	0.23
3	Guj. Cot. - 23 x Sanjay (CJ-73)	-1.62*	-0.4	-4.59	0.3	-0.26	-2.56	-0.34	-22.59*	1.84	-1.04*	-0.43	0.32
4	Guj. Cot. - 23 x Guj. Cot. – 15	-3.24**	-6.62**	9.30**	-0.08	2.50*	2.72	0.14	-6.45	-1.59	0.08	0.003	-1.13**
5	GJHV-503 x Deviraj	-0.99	-5.93**	-7.08*	0.04	0.63	-3.32	-0.35	-37.60**	-0.51	-0.45	0.09	1.25**
6	GJHV-503 x V-797	2.68**	6.79**	0.95	0.36	-0.12	-4.22*	-0.41*	-10.45	0.92	0.36	0.55	0.13
7	GJHV-503 x Sanjay (CJ-73)	1.46	4.18*	13.15**	-0.24	-1.52	6.79**	-0.12	7.10	-0.70	0.30	-0.54	-0.26
8	GJHV-503 x Guj. Cot. -15	-3.15**	-5.04**	7.02*	-0.16	1.01	0.75	0.87**	40.94**	0.29	-0.22	-0.10	-1.12**
9	761H20 x Deviraj	-1.4	-3.43*	6.89*	-0.30	-0.68	0.52	0.07	40.66**	1.25	1.59**	1.08**	-0.13
10	761H20 x V-797	-2.4**	-5.70**	-7.61**	-0.45*	-0.77	-1.25	0.74**	-50.94**	0.38	-1.41**	-0.65*	0.75*
11	761H20 x Sanjay (CJ-73)	-0.62	-2.32	-10.25**	0.35	-0.11	4.88*	0.57**	-4.92	-2.34	1.09**	-0.30	-0.27
12	761H20 x Guj. Cot. – 15	4.43**	11.46**	10.98**	0.40*	1.56	-4.16*	0.11	15.20	0.71	-1.27**	-0.13	-0.35
13	GJC-101 x Deviraj	-0.74	5.65**	-8.10*	0.65**	-0.38	-2.61	0.27	-7.02	0.30	-0.72	-0.98**	0.23
14	GJC-101 x V-797	-0.74	-2.29	14.24**	-0.33	0.19	7.29**	0.82**	33.71**	-0.15	-0.76	0.40	-0.13
15	GJC-101 x Sanjay (CJ-73)	-1.26	-0.24	6.40*	0.100	2.79**	-3.77	0.12	16.29	0.42	-0.02	0.40	-0.87**
16	GJC-101 x Guj. Cot. – 15	2.76**	-3.12*	-11.68**	-0.42*	-2.60*	-0.90	-1.21**	-42.99**	-0.57	1.50**	0.21	0.77**
17	GJHV-510 x Deviraj	2.85**	-3.68*	-11.59**	-1.17**	1.56	4.36*	0.10	36.50**	1.86	-0.78	-0.18	-1.54**
18	GJHV-510 x V-797	-0.81	-3.96*	6.61*	1.18**	1.41	-4.13*	0.63**	-8.23	-5.20**	0.71	-0.98**	0.78**
19	GJHV-510 x Sanjay (CJ-73)	1.62*	0.10	10.57**	0.12	0.48	-3.78	-0.41*	1.44	1.35	0.17	0.97**	0.34
20	GJHV-510 x Guj. Cot. – 15	-3.65**	7.54**	-5.59	-0.13	-3.45**	3.59	-0.32	-2.70**	1.99	-0.09	0.19	0.42
21	GJHV-517 x Deviraj	-1.65*	4.90**	15.15**	0.12	-0.43	0.081	0.33	-29.99**	0.20	0.17	-0.12	-0.38
22	GJHV - 517 x V-797	-1.65*	0.62	-3.87*	0.11	0.88	3.44	-0.92**	4.32	1.21	0.34	0.35	1.77**
23	GJHV-517 x Sanjay (CJ-73)	0.46	-1.32	-15.29**	-0.62**	-1.38	-1.56	0.18	2.67	-0.57	-0.50	-0.06	0.74*
24	GJHV-517 x Guj. Cot. - 15	2.85**	-4.21**	4.00	0.39*	0.92	-1.96	0.41*	22.10*	-0.84	-0.01	-0.18	1.41**
SE± (sca)		0.77	1.55	2.78	0.19	1.03	2.04	0.18	9.77	1.20	0.39	0.30	0.29
CD @ 5% (sca)		1.54	3.11	5.60	0.38	2.07	4.11	0.36	19.66	2.42	0.79	0.60	0.58
CD @ 1% (sca)		2.06	4.16	7.47	0.50	2.76	5.49	0.48	26.24	3.22	1.05	0.80	0.77

fied were: GJHV503 × Guj. Cot. - 15 – Exhibited the highest SCA impacts on the production of seed cotton, as well as positive effects for boll production. 761H20 × Deviraj – A promising hybrid for seed cotton yield, lint index, and seed index. GJC-101 × V-797 – Showed strong performance in boll production and boll weight. These hybrids hold potential for breeding programs targeting yield improvement, fiber quality, and enhanced agronomic traits in cotton.

Gene action for earliness and yield-related traits

The gene action that controls how different cotton characteristics are inherited is essential in identifying the most suitable breeding strategy. The variance estimates for specific combining ability (SCA) and general combining ability (GCA) provide insights into whether a trait is primarily influenced by additive or non-additive genetic effects. The present study revealed that traits such as DFF, SPP, GP, and LI exhibited additive gene action, indicating their potential for improvement through selection-based breeding approaches (Table 6). These findings are supported by Khan *et al*. (2024), who reported similar genetic behaviour for these traits in *G. hirsutum*. The predominance of additive effects in these traits indicates that parental performance is a good predictor of hybrid performance, making pedigree breeding, recurrent selection, and pure-line selection viable strategies for their enhancement.

On the other hand, traits like DBB, PH, MPP, BPP, BW, SYP, SI, and OC were primarily controlled by Non-Additive gene action, implying that dominance and epistatic interactions significantly contribute to their expression (Table 7). This suggests that hybrid vigor (heterosis) and hybrid breeding programs would be more effective for improving these traits rather than conventional selection methods.

Non-additive gene action is typically influenced by interactions between alleles at different loci, meaning that the selection of superior hybrids or composite varieties would be a more efficient breeding strategy than direct selection in early generations. The present study found that, with the exception of sympodia per plant, bolls per plant, and boll weight, the GCA/SCA ratio was less than unity, suggesting that non-additive gene action predominates in the inheritance of most traits studied Hamed and Said (2021); Hamed *et al*. (2024) (Fig. 1).

Among the yield-related traits, Seed cotton yield per plant, Number of bolls per plant, and Boll weight exhibited non-additive gene action, indicating the potential for heterosis breeding in enhancing productivity. Futhermore, the present study observed higher variance due to SCA than GCA in several traits, reaffirming the suitability of hybrid development through exploitation of dominance and epistasis. These findings are supported by Amna et al. (2023), who reported similar patterns in cotton hybrids. Additionally, the present results showed that testers made significant contributions to traits like ginning percentage and lint index, underlining the importance of male parents' influence on fibre-related characteristics (Table 3). This observation is consistent with the findings of Abd El-Mageed et al. (2022) who highlighted of parental influence on fibre quality improvement.

Although the findings of the present study are in agreement with earlier reports by Amna *et al*., (2023), Ali *et al*., (2024), and Khan *et al*., (2024), it offers novel insights by evaluating a unique set of six parental lines (Guj. Cot. – 23, GJHV-503, 761H20, GJC-101, GJHV-510, GJHV-517) and four testers (Deviraj, V-797, Sanjay (CJ-73), Guj. Cot. – 15), resulting in 24 diverse hybrids through a Line x Tester mating design under the specific agro-climatic conditions of Punjab during Kharif 2024. The use of diverse genotypes, particularly promising local and regional cultivars like *Guj. Cot.-23*, *761H20*, and *GJHV-510*, in a line × tester mating design, provided new evidence on combining ability patterns and heterosis for traits related to earliness, plant architecture, yield components, and seed quality. Moreover, the study integrates both earliness traits and seed-based economic traits such as lint index and oil content, which are rarely addressed together in hybrid cotton improvement. These findings not only validate previous research but also generate location-specific recommendations for hybrid development and parental selection in cotton breeding programs targeting enhanced productivity, maturity, and seed value traits in *G. hirsutum*.

Conclusion

The study identified promising parental lines and hybrids for upland cotton (*G. hirsutum* L.) improvement, focusing on combining ability, gene action, and heterosis. Significant variability was observed for yield and fiber traits, with non-additive gene action dominating for yield and fiber quality traits, while additive gene action was prominent for earliness. The top-performing hybrids, including 761H20 × V-797 and GJHV-503 × Guj. Cot.-15, exhibited strong potential for heterosis breeding, improving cotton yield and fiber quality. The best general combiners, 761H20, GJHV-510, and GJHV-517, along with promising testers like Sanjay (CJ-73) and Guj. Cot. – 15, were key contributors. For yield traits, non-additive gene action predominates, supporting heterosis breeding, while additive gene action in fibre traits favours recurrent selection. These findings offer valuable genetic resources for enhancing cotton productivity and sustainability.

Conflict of interest

The authors declare that they have no conflict of interest.

REFERENCES

1. Abd El-Mageed, T. A., & El-Sayed, M. A. (2022). Genetic analysis of yield traits in Egyptian cotton crosses using line × tester analysis. *Agricultural Research Journal*, 58(4), 456 –463. https://doi.org/10.1186/s12870□022□03839□8.
2. Amna, Shakeel, A., Farooq, M., & Xia, Y. (2023). Combining ability and heterosis for seed cotton yield, its components, and quality traits in *Gossypium hirsutum* L. *Pakistan Journal of Agricultural Research,* 36(3), 209-218.
3. Ali, S. A., & Hussain, M. (2024). Heterosis and combining ability studies for yield and quality traits in cotton. *Field Crops Research*, 275, 82-90.
4. Bhimireddy, S., Sivakami, R., Premalatha, N., Manikanda, B. N., Thirukumaran, K., & Manivannan,
5. (2023). Combining ability and gene action studies for yield and fibre traits in Gossypium arboreum using Griffing's numerical and Hayman' graphical approach. *Journal of Cotton Research,* 6(1), 1-9. https://doi.org/10.21203/rs.3.rs-2863320/v1
6. Bilwal, B. B., Vadodariya, K. V., Rajkumar, B. K., Lahane, G. R., & Shihare, N. D. (2018). Combining ability analysis for seed cotton yield and its component traits in cotton (Gossypium hirsutum L.). *International Journal of Current Microbiology and Applied Sciences,* 7(7), 3005–3010. https://doi.org/10.20546/ijcmas.2018.707.351
7. Directorate of Economics and Statistics, Department of Agriculture & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India. (2023). Cotton statistics
8. Faldu, G. O., Sanghani, A. O., Parmar, N., Ramani, H. R., & Patel, R. R. (2024). Heterosis for yield related traits, fiber quality traits and biochemical parameter in cotton [*Gossypium hirsutum* (L.)]. *International Journal of Advanced Bio chemistry Research*, 8(8), 255 -259. https://doi.org/10.33545/26174693.2024.v8.i8d.1792.
9. Fonseca, S., & Peterson, F.L. (1968). Hybrid vigour in a seven parent diallel crosses in common winter wheat (Triticum aestivum L.). Crop Science, 8(1), 85- 88. https://doi.org/10.2135/cropsci1968.0011183X000800010025x.
10. Hamed, H. H., & Said, S. R. N. (2021). Estimation of heterosis and combining ability for yield and fiber quality traits by using line x tester analysis in cotton (*Gossypium barbadense* L.). *Menoufia Journal of Plant Production*, 6(1), 35-51.
11. Hamed, M., Darwesh, A. E. I., Elfeki, F. E., Mahmoud, B. A., El-Twab, A., & Mohamed, R. (2024). Estimation of combining ability, heterosis, and heritability for some yield, yield components and fiber quality traits in cottons (*Gossypium barbadense* L.). *Menoufia Journal of Plant Production*, 9(8), 285-300.
12. Hussain, N., Abbas, A., Hammad, M., Rehman, A., Ali, T., Ashraf, S., & Javed, M. (2023). Combining ability and heterosis estimates for traits in upland cotton (*Gossypium hirsutum* L.). *Journal of Plant Breeding*, 12(1), 45–55.
13. Keerthivarman, K., Mahalingam, L., Premalatha, N., Boopathi, N. M., Senguttuvan, K., & Manivannan, A. (2022). Combining ability and heterosis studies in cotton (Gossypium hirsutum L.) for yield and fibre quality traits. *Electronic Journal of Plant Breeding*, 13(2), 697-704.
14. Kempthrone, O. (1957). An Introduction to Genetics Statistics. John Willey and Sons. New York. pp. 453-471.
15. Khan, M. M., & Ahmad, N. (2024). Genetic analysis of cotton yield and fiber traits using diallel cross. *Journal of Agricultural Sciences*, 59(1), 65-74.
16. Madugula, S. R., Chapara, R., Reddy, K. S., Lakshmi, B. S., & Pranaya, J. (2023). Combining ability and heterosis studies for seed cotton yield and fibre quality traits in cotton. Electronic Journal of Plant Breeding, 14(2), 439-447. https://doi.org/10.37992/2023.1402.044
17. Malathi, S., Patil, R. S., & Shankarappa, S. H. (2019). Heterosis studies in interspecific cotton hybrids (Gossypium hirsutum L. × Gossypium barbadense L.) under irrigated condition. *Electronic Journal of Plant Breeding,* 10(2), 852–858.
18. Panse, V. G., & Sukhatme, P.V. (1985). Statistical methods for agricultural research. ICAR, New Delhi, 8, 308-318.
19. Patel, A., Chaudhari, K. N., Fladu, G. O., Patel, S., Mahla, J. S., Prajapati, M. R., & Patel, D. P.
20. (2024). Heterosis and Inbreeding Depression Studies for Fibre Quality Traits in Upland Cotton (Gossypium hirsutum L.). *Journal of Advances in Biology & Biotechnology*, 27(9), 477-484. https://doi.org/10.9734/jabb/2024/v27i91319.
21. Rakesh, Choudhary., Solanki, B. G., Navin Chander Gahtyari., Tapas Paul and Patel, D. M. (2016). Heterosis in single cross inter and intra-specific hybrids of Desi cotton (Gossipium arboreum and G. herbaceaum) for their seed cotton yield, fibre quality and seed oil content. *Journal of Applied and Natural Science*, 8(3), 1356-1365.
22. Rakesh, S., Ganvit., Kamleshkumar, N., Chaudhari., Rajesh, J., Panchal., Hardik, R. Patel., & Ashita Patel. (2024). Combining ability and gene action studies for yield and its component traits over different environments in cotton (G. hirsutum L*.), Biological Forum*, 16(4), 154-165.
23. Rao, N. S., Sireesha, E., Kumar, D. S., & Kumari, C. R. (2024). A front-line demonstration on integrated pest management in cotton with special reference to pink boll worm, *Pectinophora gossypiella* (Saunders) and its economic analysis under farmer's field conditions. *International Journal of Advanced Biochemistry Research*, **8**(2), 297–300. https://doi.org/10.33545/26174693.2024.v8.i2d.592
24. Richika, R., Rajeswari, S., Premalatha, N., & Thirukumaran, K. (2021). Heterosis and combining ability analysis for yield contributing traits and fibre quality traits in interspecific cotton hybrids (Gossypium hirsutum L. x Gossypium barbadense L.). *Electronic Journal of Plant Breeding,* 12 (3), 934-940.
25. Shahzad, K., Iqra, M., Zhang, M., Zhang, X., Wu, J., & Xing, C. (2022). Progress and perspective on cotton breeding in Pakistan. *Journal of Cotton Research*, 5(29). https://doi.org/10.1186/s42397-022-00137-4.
26. Singh, A. K., & Kumar, S. (2024). Evaluation of combining ability for yield and fiber quality traits in cotton (Gossypium hirsutum L.). Electronic Journal of Plant Breeding, 15(1), 22-30.
27. Singh, R.K., & Chaudhary, B.D. (1985). Biometrical Methods in Quantitative Genetic Analysis. Kalyani Publishers,

New Delhi.
28. Singh, R.K., & Chaudhary, B.D., (1977). Biometrical methods in quantitative genetic analysis. Kalyani Publishers, New Delhi.
29. Solangi, A. H., Kayande, N. V., & Shinde, J. V. (2025). Combining ability study for seed cotton yield and attributing traits in american cotton (Gossypium hirustum L.). *International Journal of Advanced Biochemistry Research,* 9(3), 275-279 .https://doi.org/10.33545/26174693.2025.v9.i3Sd.3948
30. Venkatesan, T., Anandan, K., Hari Ramakrishnan, S., Nallathambi, P., & Ramadoss, B. R. (2024). Genetic variability of Asiatic cotton (Gossypium arboreum L.) germplasm for yield and surgical cotton properties. *Industrial Crops and Products*, 219, 119065.
31. Vanapariya, S. J., Faldu, G. O., Patel, R. R., Viradiya, B. R., & Rana, V. B. (2024) Combining ability and gene action analysis in intraspecific hybrids of cotton (Gossypium hirsutum L.). Plant Archives, 24(1), 1195-1202.https://doi.org/10.51470/PLANTARCHIVES.2024.v24.no.1.166.
32. Zhang, L., Sun, H., & Wang, X. (2024). Combining ability and heterosis analysis for seed cotton yield and fiber quality traits in Gossypium hirsutum. *Industrial Crops and Products*, 206, 1-9.