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Genetic evaluation of yield and fibre quality traits in Bt cotton (*Gossypium hirsutum* L.) using line × tester mating design

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Abstract
The present study was carried out at the Cotton Research Unit, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, to assess heterosis and combining ability for yield and fibre quality traits in Bt cotton. A total of 10 F1 hybrids, developed through a line × tester mating design involving two female lines and five male testers during kharif 2023, were evaluated along with 7 parents and four standard checks in a randomized block design with two replications during kharif 2024. Significant variation was observed among genotypes for all traits studied, indicating substantial genetic diversity. Among the hybrids, AKBt-6 X AKBt-206 exhibited the highest standard heterosis for seed cotton yield over the best check (Rasi Swift). In terms of fibre quality traits, here also AKBt-6 X AKBt-206 showed superior performance for upper half mean length and fibre strength. AKBt-96 X AKBt-14 demonstrated the most desirable negative heterosis for fibre fineness. General combining ability (GCA) analysis revealed AKBt-6 as strong general combiner among female for yield and quality traits, while AKBt-206 showed favorable GCA effects for most of the yield and fibre quality traits. Specific combining ability (SCA) analysis identified AKBt-96 X AKBt-14, AKBt-6 X AKBt-212 and AKBt-6 X AKBt-206 as promising crosses for yield and fibre attributes. These findings provide valuable insights for selecting superior hybrids and parents for cotton improvement programms.

Keywords: Bt cotton, heterosis, combining ability, line x tester, seed cotton yield, Fibre Quality, GCA, SCA.

Introduction
Cotton (*Gossypium spp*.), known as the "White Gold," is a major cash crop with significant potential for rural and urban employment. In India, it remains the leading fiber crop and a key commercial commodity. Besides lint, the crop provides oil, seed meal, linters, and hulls, making it highly multifunctional. Cotton stalks are also used as fuel and for producing paper and particle boards.

The main objective of cotton breeding is to develop new Bt hybrids and varieties with high yield potential and superior fibre quality. The wide genetic diversity present in cotton germplasm serves as a valuable resource for creating improved genotypes with better productivity and fibre characteristics. Cotton is particularly well-suited for harnessing hybrid vigour through heterosis breeding. In recent years, greater focus has been given to intraspecific hybridization, which involves crossing different lines within the same species to enhance desirable traits.

Combining ability refers to the capacity of parents or cultivars to interact during hybridization in such a way that favorable genes or characters are transmitted to their offspring. In quantitative genetics, two distinct types of combining ability are recognized: general combining ability (GCA) and specific combining ability (SCA). GCA denotes the average performance of a line across a range of crosses, while SCA represents the deviation of a hybrid's performance from the expected productivity, based on the average performance of the parental lines involved in the cross.

Materials and Methods
The study was conducted at the Cotton Research Unit, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola. During kharif 2023, two female parents (lines) were crossed with five testers in a line × tester design, producing ten F_1 hybrids. These hybrids, along with seven

parents and four standard checks, were evaluated in a randomized block design with two replications during kharif 2024. Recommended agronomic practices were followed, and data on five plants per genotype per replication were recorded for yield traits i.e. number of bolls per plant, boll weight (g), seed cotton yield per plant (g) and fibre quality traits i.e. upper half mean length (mm), fibre strength (g/tex) and fibre fineness (µg/ inch). Analysis of variance (ANOVA) were performed according to the methods outlined by Panse and Sukhatme (1954) [12]. Analysis of standard heterosis carried out as per standard method given by Meredith and Bridge (1972) [10]. ANOVA for combining ability was based on the methodology given by Kempthorne (1957) [5].

Results and Discussion

In the current investigation, the analysis of variance (ANOVA) revealed statistically significant differences among genotypes for all traits evaluated, indicating the presence of substantial genetic variability among the genotypes for each character studied.

Estimates of standard heterosis

The magnitude of standard heterosis for number of boll per plants over Rasi Swift varied from −21.31% to 44.26%, with AKBt-6 × AKBt-206 (44.26%) and AKBt-6 × AKBt-1 (27.87%) exhibiting significant positive heterosis. Over Money Maker, AKBt-6 × AKBt-206 (72.55%) and AKBt-6 × AKBt-1 (52.94%) showed the highest standard heterosis, while over Ankur Kirti, only AKBt-6 × AKBt-206 (31.34%) was significant in desirable direction. For ARCH-3106, AKBt-6 × AKBt-206 (46.67%) and AKBt-6 × AKBt-1 (30.00%) recorded the highest standard heterosis values.

For boll weight, standard heterosis over Rasi Swift varied from −8.16% to 39.80%, with AKBt-6 × AKBt-206 (39.80%) showing the highly significant heterosis, followed by AKBt-96 × AKBt-14 (34.69%) in desirable direction. Over ARCH-3106, standard heterosis ranged from −18.18% to 24.55%, with only AKBt-6 × AKBt-206 (24.55%) exhibiting positively significant standard heterosis.

The magnitude of standard heterosis for seed cotton yield over Rasi Swift ranged from −54.05% to 33.98% with only AKBt-6 × AKBt-206 (33.98%) showing a significant positive value. Over Money Maker, standard heterosis ranged from −31.21% to 100.58% with AKBt-6 × AKBt-206 (100.58%) recording the highest standard heterosis, followed by AKBt-6 × AKBt-1 (45.66%) and AKBt-6 × AKBt-14 (36.99%). Similarly, over Ankur Kirti, standard heterosis varied from −51.43% to 41.63%, with AKBt-6 × AKBt-206 (41.63%) being the only significant cross in desirable direction. For ARCH-3106, standard heterosis ranged from -40.80% to 72.64%, with AKBt-6 × AKBt-206 (72.64%) again recording the highest value, followed by AKBt-6 × AKBt-1 (25.37%).

Standard heterosis estimates for upper half mean length over Rasi Swift varied from −3.86% to 8.77% with AKBt-6 × AKBt-206 (8.77%) recording the highest value, followed by AKBt-6 × AKBt-1 (8.07%). Over Money Maker, standard heterosis ranged from −8.36% to 3.68% with AKBt-6 × AKBt-206 (3.68%) again showing the highest positive value, followed by AKBt-6 × AKBt-1 (3.01%). However, for checks Ankur Kirti and ARCH-3106, where standard heterosis ranged from −11.04% to 0.65% and −11.61% to 0.00% respectively, none of the hybrids exhibited significant positive heterosis.

The estimates of Standard heterosis for fibre strength over Rasi Swift ranged from 1.89% to 16.60%, where AKBt-6 × AKBt-206 (16.60%) recorded the maximum heterosis, followed by AKBt-6 × AKBt-27 (15.09%). Over Money Maker, standard heterosis ranged between −8.47% and 4.75%, with AKBt-6 × AKBt-206 (4.75%) showing the highest positive heterosis, followed by AKBt-6 × AKBt-27 (3.39%) and AKBt-96 × AKBt-14 (3.05%). In contrast, for Ankur Kirti, where the range was −13.18% to −0.64%, none of the crosses exhibited significant heterosis in the desirable direction. Similarly, over ARCH-3106, heterosis ranged from −6.57% to 6.92%, with AKBt-6 × AKBt-206 (6.92%) showing the maximum value, followed by AKBt-6 × AKBt-27 (5.54%) and AKBt-96 × AKBt-14 (5.19%).

Table 1: Estimates of Standard heterosis over check (Rasi Swift, Money Maker, Ankur Kirti, ARCH-3106)

Sr. No.	Hybrids	Number of bolls per plant				Boll weight (g)				Seed cotton yield (g/plant)			
		Rasi Swift	Money Maker	Ankur Kirti	ARCH-3106	Rasi Swift	Money Maker	Ankur Kirti	ARCH-3106	Rasi Swift	Money Maker	Ankur Kirti	ARCH-3106
1	AKBt-6 x AKBt-1	27.87 *	52.94 **	16.42	30.00 *	17.35	-4.17	-0.86	4.55	-2.70	45.66 **	2.86	25.37 *
2	AKBt-6 x AKBt-14	14.75	37.25 *	4.48	16.67	10.20	-10.00	-6.90	-1.82	-8.49	36.99 *	-3.27	17.91
3	AKBt-6 x AKBt-27	4.92	25.49	-4.48	6.67	-8.16	-25.00 *	-22.41 *	-18.18	-12.74	30.64 *	-7.76	12.44
4	AKBt-6 x AKBt-206	44.26 **	72.55 **	31.34 **	46.67 **	39.80 **	14.17	18.10	24.55 *	33.98 **	100.58 **	41.63 **	72.64 **
5	AKBt-6 x AKBt-212	-3.28	15.69	-11.94	-1.67	18.37	-3.33	0.00	5.45	-10.04	34.68 *	-4.90	15.92
6	AKBt-96 x AKBt-1	13.11	35.29 *	2.99	15.00	10.20	-10.00	-6.90	-1.82	-31.27 **	2.89	-27.35 **	-11.44
7	AKBt-96 x AKBt-14	-8.20	9.80	-16.42	-6.67	34.69 *	10.00	13.79	20.00	-38.22 **	-7.51	-34.69 **	-20.40
8	AKBt-96 x AKBt-27	-16.39	0.00	-23.88 *	-15.00	8.16	-11.67	-8.62	-3.64	-50.58 **	-26.01	-47.76 **	-36.32 **
9	AKBt-96 x AKBt-206	9.84	31.37 *	0.00	11.67	20.41	-1.67	1.72	7.27	-15.06	27.17 *	-10.20	9.45
10	AKBt-96 x AKBt-212	-21.31	-5.88	-28.36 *	-20.00	25.51	2.50	6.03	11.82	-54.05 **	-31.21 *	-51.43 **	-40.80 **
	SE (d)	3.0667	3.0667	3.0667	3.0667	0.5540	0.5540	0.5540	0.5540	10.0132	10.0132	10.0132	10.0132
	CD at 5%	6.9372	6.9372	6.9372	6.9372	1.2531	1.2531	1.2531	1.2531	22.6513	22.6513	22.6513	22.6513
	CD at 1%	9.9661	9.9661	9.9661	9.9661	1.8003	1.8003	1.8003	1.8003	32.5412	32.5412	32.5412	32.5412

* Significant at 5% level of significance ** Significant at 1% level of significance

Sr. No.	Hybrids	Upper half mean length (mm)				Fibre strength (g/tex)				Fibre fineness (µg/inch)			
		Rasi Swift	Money Maker	Ankur Kirti	ARCH-3106	Rasi Swift	Money Maker	Ankur Kirti	ARCH-3106	Rasi Swift	Money Maker	Ankur Kirti	ARCH-3106
1	AKBt-6 x AKBt-1	8.07**	3.01**	0.00	-0.65	11.70**	0.34	-4.82**	2.42	-13.00**	0.00	-4.40*	1.16
2	AKBt-6 x AKBt-14	4.56**	-0.33	-3.25**	-3.87**	5.66**	-5.08**	-9.97**	-3.11*	-5.00**	9.20**	4.40*	10.47**
3	AKBt-6 x AKBt-27	7.37**	2.34**	-0.65	-1.29	15.09**	3.39*	-1.93	5.54**	-11.00**	2.30	-2.20	3.49*
4	AKBt-6 x AKBt-206	8.77**	3.68**	0.65	0.0	16.60**	4.75**	-0.64	6.92**	-14.00**	-1.15	-5.49**	0.0
5	AKBt-6 x AKBt-212	7.37**	2.34**	-0.65	-1.29	6.79**	-4.07**	-9.00**	-2.08	-8.00**	5.75**	1.10	6.98**
6	AKBt-96 x AKBt-1	-3.86**	-8.36**	-11.04**	-11.61**	10.57**	-0.68	-5.79**	1.38	-8.00**	5.75**	1.10	6.98**
7	AKBt-96 x AKBt-14	4.56**	-0.33	-3.25**	-3.87**	14.72**	3.05*	-2.25	5.19**	-19.00**	-6.90**	-10.99**	-5.81**
8	AKBt-96 x AKBt-27	2.11**	-2.68**	-5.52**	-6.13**	13.96**	2.37	-2.89*	4.5**	-16.00**	-3.45*	-7.69**	-2.33
9	AKBt-96 x AKBt-206	7.72**	2.68**	-0.32	-0.97	6.79**	-4.07**	-9.00**	-2.08	-16.00**	-3.45*	-7.69**	-2.33
10	AKBt-96 x AKBt-212	-1.75*	-6.35**	-9.09**	-9.68**	1.89	-8.47**	-13.18**	-6.57**	-4.00*	10.34**	5.49**	11.63**
	SE (d)	0.1776	0.1776	0.1776	0.1776	0.3132	0.3132	0.3132	0.3132	0.0639	0.0639	0.0639	0.0639
	CD at 5%	0.4018	0.4018	0.4018	0.4018	0.7085	0.7085	0.7085	0.7085	0.1445	0.1445	0.1445	0.1445
	CD at 1%	0.5772	0.5772	0.5772	0.5772	1.0178	1.0178	1.0178	1.0178	0.2076	0.2076	0.2076	0.2076

* Significant at 5% level of significance ** Significant at 1% level of significance

For fibre finenss, the magnitude of standard heterosis over check Rasi Swift ranged from -19.00 to -4.00 per cent, with AKBt-96 x AKBt-14 (-19.00%) showed lowest desirable standard heterosis. Over the check Money Maker it ranged from -6.90 to 10.34 per cent and the cross AKBt-96 x AKBt-14 (-6.90%) showed lowest desirable standard heterosis. The estimates of standard heterosis over Ankur Kirti ranged from -10.99 to 5.49, the hybrid AKBt-96 x AKBt-14 (-10.99%) showed lowest desirable standard heterosis over Ankur Kirti. Standard heterosis over ARCH-3106 ranged from -5.81 to 11.63 per cent. Only one hybrid AKBt-96 x AKBt-14 (-5.81%) showed negatively significant standard heterosis out of ten test hybrids over this check.

Similar finding for standard heterosis for these characters in cotton was also reported earlier by several researchers viz., Rauf *et.al* (2005) [16], Tuteja *et al.* (2006) [22], Isong *et al.* (2019) [3] for seed cotton yield per plant, Tuteja (2014) [21], Pavitra *et al.* (2019) [14] and Bano *et al.* (2023) [2] for upper half mean length, fibre strength, fibre fineness and uniformity ratio.

Estimates of general combining ability effect of parents

For the number of bolls per plant, the female parent AKBt-6 (3.400) was identified as the best general combiner, exhibiting the positively significant GCA effect. Among the male parents, AKBt-206 (6.250) recorded the highly significant GCA effect in desirable direction, followed by AKBt-1 (4.250), indicating their potential for improving this trait. In contrast, AKBt-212 (−5.750) showed a significant negative GCA effect, suggesting its poor combining ability for the number of bolls per plant.

Among the female parents, none of the parent showed positive significant gca effect for boll weight. AKBt-96 (0.105) showed highest non-significant gca effect in desirable direction. Among the male parents, none of the parent showed positively significant gca effect for boll weight, while AKBt-206 (0.610) has highest non-significant gca effect in desirable direction.

Table 2: Estimates of general combining ability effects of parents

Sr. No.	Parents	Number of bolls/plant	Boll weight (g)	Seed cotton yield g/plant	Upper half mean length (mm)	Fibre strength (g/tex)	Fibre fineness (µg/inch)
Lines (Female)							
1	AKBt-6	3.400 **	-0.105	24.500 **	0.780**	0.210	0.060*
2	AKBt-96	-3.400 **	0.105	-24.500 **	-0.780**	-0.210	-0.060*
	SE (gi)	0.9698	0.1752	3.1665	0.0562	0.0990	0.0202
	CD at 5%	2.1937	0.3963	7.1630	0.1271	0.2240	0.0457
	CD at 1%	3.1516	0.5693	10.2904	0.1825	0.3219	0.0657
Tester (Male)							
1	AKBt-1	4.250 *	-0.190	2.500	-0.680**	0.200	0.045
2	AKBt-14	-1.000	0.235	-5.750	0.020	0.050	-0.030
3	AKBt-27	-3.750 *	-0.865*	-16.500 **	0.070	1.100**	-0.105**
4	AKBt-206	6.250 **	0.610	36.750 **	1.070**	0.350	-0.180**
5	AKBt-212	-5.750 **	0.210	-17.000 **	-0.480**	-1.600**	0.270**
	SE (gi)	1.5333	0.2770	5.0066	0.0888	0.1566	0.0319
	CD at 5%	3.4686	0.6266	11.3257	0.2009	0.3542	0.0723
	CD at 1%	4.9831	0.9001	16.2706	0.2886	0.5089	0.1038

* Significant at 5% level of significance ** Significant at 1% level of significance

For seed cotton yield per plant, Among the female parents, AKBt-6 (24.500) was found to be the best general combiner. Among the male parents, only AKBt-206 (36.750) depicted the highest positive and significant gca effects and hence rank to be best general combiner among the males for seed cotton yield per plant.

In upper half mean length, among the female parents, AKBt-6 (0.780) showed positively significant gca effect. Similarly, among testers, AKBt-206 (1.070) showed highly significant gca effect in desirable direction and was found best general combiner among the five male parents.

For fibre strength, none of the female parents expressed positively significant gca effects for this trait. However, AKBt-6 (0.210) expressed highest non-significant gca effect among the lines. Among the testers, AKBt-27 (1.100) was the only male, which showed significant positive gca effect and it was found to be a good general combiner for fibre strength.

In case of fibre fineness, among the female parents, AKBt-96 (-0.060) line exhibited negatively significant gca effects which is desirable for this trait and ranked it to be best general combiner for this trait. Among the set of testers, two testers showed significant negative gca effects viz., AKBt-206 (-0.180) and AKBt-27 (-0.105).

Similar type of results reported by Manickam and Gururajan (2004) [9], Sakhare *et al*. (2005) [18], Khosla *et al.* (2007) [7], Preetha and Raveendran (2008) [15], Saravanan *et al.* (2010) [19], Patel *et al*. (2012) [13], Jaiwar *et.al*. (2012) [4], Sawarkar *et al*. (2015) [20], Usharani *et al*. (2016) [23] and Khokhar *et al*. (2018) [6], Mangi *et al*. (2024) [8], Riaz *et.al*. (2023) [17] and Baghyalakshmi *et al.* (2023) [1] for evaluated traits.

Estimates of specific combining ability effect of crosses

Among the ten crosses evaluated, none exhibited a significant positive SCA effect for the number of bolls per plant. However, the cross AKBt-6 × AKBt-206 (1.850) recorded the highest, though non-significant, SCA effect, followed by AKBt-96 × AKBt-1 (1.150)**.** Similarly, no cross showed a significant positive SCA effect for boll weight and seed cotton yield. In contrast, for upper half mean length, four crosses exhibited significant SCA effects in the desirable direction. Notably, the cross AKBt-6 × AKBt-1 (0.920) recorded the highest significant positive SCA effect, followed by AKBt-96 × AKBt-14 (0.780).

Two crosses exhibited significant positive SCA effects for fibre strength, with AKBt-96 × AKBt-14 (1.410) showing the highest significant positive SCA effect, followed by AKBt-6 × AKBt-206 (1.090). For fibre fineness, three hybrids among the ten crosses showed significant SCA effects in the desirable direction. The cross AKBt-96 × AKBt-14 (-0.290) recorded the highest significant negative SCA effect, followed by AKBt-6 × AKBt-1 (-0.185) and AKBt-6 × AKBt-212 (-0.160).

Khosla *et al*. (2007) [18], Baghyalakshmi *et al.* (2023) [1] reported sca effect in desirable direction for upper half mean length. Mudhalvan *et al*. (2021) [11], Mangi *et al*. (2024) [8] and Vanapariya *et al.* (2024) [24] also reported sca effect in desirable direction for number of bolls per plant, boll weight and seed cotton yield.

Table 2: Estimates of specific combining ability effects of crosses.

Sr. No.	Parents	Number of bolls/plant	Boll weight (g)	Seed cotton yield g/plant	Upper half mean length (mm)	Fibre strength (g/tex)	Fibre fineness (u g/inch)
1	AKBt-6 x AKBt-1	1.210**	0.178	-6.000	0.920**	-0.060	-0.185**
2	AKBt-6 x AKBt-14	-1.115**	-0.313*	-5.250	-0.780**	-1.410**	0.290**
3	AKBt-6 x AKBt-27	-0.340	-0.215	-6.300	-0.030	-0.060	0.065
4	AKBt-6 x AKBt-206	0.135	-0.035	7.250	-0.630**	1.090**	-0.010
5	AKBt-6 x AKBt-212	0.110	0.385*	4.000	0.520**	0.440	-0.160**
6	AKBt-96 x AKBt-1	-1.210**	-0.178	6.000	-0.920**	0.060	0.185**
7	AKBt-96 x AKBt-14	1.115**	0.313*	5.250	0.780**	1.410**	-0.290**
8	AKBt-96 x AKBt-27	0.340	0.215	6.300	0.030	0.060	-0.065
9	AKBt-96 x AKBt-206	-0.135	0.035	-7.250	0.630**	-1.090**	0.010
10	AKBt-96 x AKBt-212	-0.110	-0.385*	-4.000	-0.520**	-0.440	0.160**
	SE (gi)	0.1562	0.1266	7.0804	0.1256	0.2215	0.0452
	CD at 5%	0.3533	0.2863	16.0169	0.2841	0.5010	0.1022
	CD at 1%	0.5076	0.4113	23.0101	0.4081	0.7197	0.1468

* Significant at 5% level of significance ** Significant at 1% level of significance

Conclusion

The present investigation revealed significant genetic among the genotypes for all traits studied, as confirmed by ANOVA. This genetic variability provides a strong foundation for breeding programs aimed at improving cotton yield and fibre quality. Several hybrids exhibited notable standard heterosis for seed cotton yield, with AKBt-6 X AKBt-206 and AKBt-96 X AKBt-14 emerging as particularly promising crosses. These combinations consistently outperformed the standard checks, indicating their potential for commercial cultivation.

In terms of fibre traits, AKBt-6 X AKBt-206 showed superior performance in upper half mean length and fibre strength while AKBt-96 X AKBt-14 recorded the most desirable negative heterosis for fibre fineness. The combining ability analysis identified, AKBt-6 among lines and AKBt-206 among testers, as strong general combiners for yield and quality attributes. Additionally, crosses such as AKBt-96 X AKBt-14, AKBt-96 X AKBt-212 and AKBt-96 X AKBt-206 exhibited significant specific combining ability for most of the traits, suggesting their suitability for hybrid development**.**

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