JOURNAL OF PLANT RESEARCH AND INNOVATIONS
Jan-Mar 2024, VOL. 2, ISSUE 1, pp- 11-19
https://doi.org/10.61577/jpri.2024.100002

RESEAPRO JOURNALS

ORIGINAL ARTICLE

OPEN ACCESS

Evaluation of hybrid potential and ability to combine early maturity, yield, and related characteristics in okra (*Abelmoschus esculentus* L. Moench)

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ABSTRACT

Evaluation of 50 lines of okra including thirteen parents, thirty-six hybrids, and one standard check (Punjab-8) in a Randomized Block Design with three replications to analyse heterotic potential and combing ability. Crosses L3 x T2 (8.28), L8 x T3 (8.46) and L9 x T3 (7.68) exhibited significant positive heterosis for yield plant-1. Same crosses L3 x T2 (-8.33, -15.94) and L9 x T3 (-4.17, -18.12) exhibited negatively significant heterosis for traits viz. days to 50% flowering and days to first picking respectively over standard check that revealed earliness traits. High heterotic potential obtained in hybrid estimates genetic divergence among the parental lines and can be commercially exploit for heterosis in okra. However, the parents L3, L2 and L9 were all excellent general combiners. Parents exhibited significant and highly negative GCA effect for days to 50% flowering and days to first picking respectively viz. L3 (-2.69, -2.39) and T1 (-0.43, -0.92). Crosses L5 x T4 (-4.19, -8.39) exhibited highest negatively significant SCA effect for days to 50% flowering and days to first picking respectively and L5 x T3 (102.79) exhibited highest positively significant SCA effect for yield plant-1. Variance to (GCA) general combining ability σ2GCA is lower than the variance to (SCA) specific combining ability σ2SCA with σ2GCA: σ2SCA ratio (< 1) less than unity indicating non-additive gene action for all the traits.

KEYWORDS

Heterosis; Standard check; General combining ability; Specific combining ability; Gene action

ARTICLE HISTORY

Received 8 January 2024;
Revised 6 February 2024;
Accepted 11 February 2024

Introduction

Okra, also known as *Abelmoschus esculentus* L. in scientific terms, is an herbaceous annual vegetable that falls under the Malvaceae family and the Malvales order. It has a chromosome number of 2n=130 and is amphidiploid. Zeven and Zhukovsky declared that the starting point was the Hindustani region, comprising India, Pakistan, and Burma. Okra, dubbed the "Queen of Vegetables," is a popular option for many people [1]. Okra is a popular vegetable plant that is frequently consumed and appreciated for its reasonable cost. It is seen as a suitable main vegetable crop in countries with lower levels of income. Lately, the global demand for okra has increased due to its nutritional benefits, resulting in a selection of okra products being offered for sale online. As per the Market Research Future report in 2020, the AMRF agency forecasts that the worldwide okra seed market will achieve USD 352.7 million in sales and grow at a rate of 9.8% annually from 2018 to 2023.

The utilization of heterosis in okra is recognized as a beneficial method to enhance yield and other important traits in breeding work. The primary objective of heterosis breeding is to enhance the productivity and quality of crops substantially. Attempts have been made to enhance productivity by concentrating on the characteristics of okra varieties and hybrids related to both output and quality. Heterosis plays a vital role in improving the economic characteristics of okra by offering valuable insights. Multiple research investigations have discovered significant levels of hybrid vigor in the timing of growth, fruit yield, and other associated aspects. Hybridization is necessary to address the production limitations of existing open-pollinated okra types. Breeding for heterosis has proven to be the most efficient way to increase productivity in cross-pollinated vegetable crops. Vijayaraghavan and Warrier were the pioneers in demonstrating the presence of heterosis in okra [2]. Anticipating and managing the anticipated boost in productivity is crucial because of the large flower size and Monadelphous stamens. Furthermore, there have been several studies that have also documented a significant presence of heterosis in okra across different characteristics linked to fruit productivity [3]. Taking this viewpoint into account, the present research aims to examine the degree and manner of standard heterosis for yield and its associated characteristics in okra.

As per Sprague and Tatum, the assessment process entails evaluating the combining potential of parent lines and their hybrids to recognize superior combining effects, referred to as general combining ability (GCA) in parents and specific combining ability (SCA) in hybrids [4]. The GCA reveals the impacts of single genes, while the SCA reveals interactions among alleles related to dominance and epistasis. SCA happens when the offspring's performance differs from what is anticipated according to the parent's GCA. Kempthorne's Line x Tester analysis method, which was initially presented in 1957, is widely respected as a highly effective and organized approach for recognizing superior parents and crosses. This method is essential for achieving success in all breeding efforts.

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Materials and Methods

The Genetics and Plant Breeding Research Farm at Lovely Professional University in Phagwara, Punjab conducted a research study in which 36 F1s were created using 13 okra genotypes (9 lines and 4 testers) and one standard check Punjab 8 (Table 1). The assessment was conducted in the Kharif 2022 season utilizing a randomized block design and three replications. Twelve unique characteristics were analyzed in five plants from both the original and F1 offspring. Some of these traits were time taken to reach half flowering and initial harvesting, length of fruit when ripe and during harvest, amount of internodes and branches, fruits produced per plant, seeds within each fruit, seed size, weight of fruit, plant productivity, and plant height.

Table 1. Parents used in crossing program with a commercial check.

S. NO	LINES (7)		TESTERS (4)		COMMERCIAL CHECK
1	9428	L1	9450	T1	Punjab 8
2	212	L2	212	T2	
3	1979	L3	551	T3	
4	8185	L4	552	T4	
5	4922	L5			
6	4008	L6			
7	4009	L7			
8	3033	L8			
9	2535	L9			

Calculation of hybrid vigor

An ANOVA was performed using the procedure detailed by Panse and Sukhatme for Randomized Block Design (RBD) to evaluate the significance of treatment variations across all measured quantitative biometric variables [5]. The performance of the F1 hybrid was assessed using the heterosis over standard check method established by Fonseca and Patterson in 1968 [6]. The evaluation of heterotic potential in both positive and negative directions was done by measuring the difference in F1 hybrids compared to standard checks, using formulas from Singh and Chaudhary presented in Table 2a [7].

Heterosis over standard check (SH)

$$\mathrm{SH\%} = \frac{\mathrm{F1} - \mathrm{SC}}{\mathrm{SC}} \mathrm{x}\ 100$$

Where SH = Standard or commercial check mean performance.

Table 2a. RBD Analysis of variance of various characters.

SOURCE	Df	DFF	DFP	PH	NI	NB	FLM	FLH	NFP	NSF	SI	FW	YP
REPLICATION	**2**	0.19	1.45	0.67	0.03	0.13	0.01	0.01	0.61	0.06	0.00	0.04	26.70
GENOTYPES	**49**	14.45*	34.59**	831.14**	5.95**	2.72**	3.61**	3.61**	20.75**	7.82**	2.26**	4.92**	8642.50**
ERROR	**98**	0.59	1.09	0.30	0.01	0.17	0.03	0.03	0.82	0.05	1.15	0.04	110.70

DFF-Days to 50% flowering, **DFP**- Days to first picking, **PH**- Plant height, **NI**- Number of internodes, **NB**- Number of branches, **FLM**- Fruit length at maturity, **FLH**- Fruit length at harvest, **NFP**- Number of fruit plant-1, **NSF**- Number of seeds fruit-1, **SI**- Seed index, **FW**- Fruit weight and **YP**- Yield plant-1

*Significant at 5 per cent level, ** Significant at 1 per cent level

Estimation of GCA and SCA effects

An investigation was carried out using ANOVA to assess combining ability through the Line x Tester approach, with significance testing for different genotypes following the criteria outlined by Kempthorne and Singh and Chaudhary as presented in Table 2b [8,9]. Through the creation of a two-way table depicting female and male parents and consolidating the outcomes from multiple repetitions, it was feasible to ascertain the distinct impacts of GCA and SCA.

(a) GCA effects of Ath line $\mathrm{Gi} = \frac{\mathrm{xA}}{\mathrm{Tr}} - \frac{\sigma\ \mathrm{x}}{\mathrm{LTr}}$

(b) GCA effects of Bth tester $\mathrm{Gj} = \frac{\mathrm{xB}}{\mathrm{Lr}} - \frac{\sigma\ \mathrm{x}}{\mathrm{LTr}}$

(c) SCA effects of ABth cross $\mathrm{Sij} = \frac{\mathrm{xAB}}{\mathrm{r}} - \frac{\mathrm{xA}}{\mathrm{T}} - \frac{\mathrm{xB}}{\mathrm{Lr}} + \frac{\sigma\ \mathrm{x.}}{\mathrm{LTr}}$

Where,

∑x. = total sum of all crosses, xA. = total sum of Ath lines over all testers and replications

xA = total of Bth tester over all lines and replications,

xAB = ABth line x tester combination total over all replications,

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

Table 2b. Analysis of variance of Line x Tester for combing ability.

SOURCE	DF	DFF	DFP	PH	NI	NB	FLM	FLH	NFP	NSF	SI	FW	YP
REPLICATION	2	0.09	1.48	210.99	17.01	0.13	0.13	0.13	0.63	113.19	0.00	0.03	32.59
GENOTYPES	48	14.49**	35.26**	847.89**	6.01**	2.77*	3.52*	3.52*	21.11**	7.88**	2.31*	4.87*	8692.80**
CROSS	35	17.44**	37.76**	876.15**	6.49**	2.96*	4.01*	4.01*	22.70**	8.20**	2.29*	4.36*	8646.86**
LINE(c)	8	30.38**	50.31**	567.22**	4.09*	0.63*	5.50*	5.50*	25.02**	2.66*	1.15*	3.76*	7038.58**
TEST(c)	3	6.28**	14.31**	730.31**	3.34*	0.35	1.73*	1.73*	9.02**	8.80**	9.51**	0.74	2731.13**
L x T (c)	24	14.52**	36.51**	997.36**	7.68**	4.06*	3.80*	3.80*	23.64**	9.97**	1.77*	5.01**	9922.41**
PARENT	12	6.52**	27.36**	826.35**	4.81*	2.34*	2.02*	2.02*	18.23**	7.10**	2.54*	6.62**	9503.69**
ERROR	96	0.59	1.12	0.10	0.01	0.17	0.03	0.03	0.83	0.05	1.17	0.04	109.88
TOTAL	146												

https://doi.org/10.61577/jpri.2024.100002

DFF-Days to 50% flowering, **DFP**- Days to first picking, **PH**- Plant height, **NI**- Number of internodes, **NB**- Number of branches, **FLM**- Fruit length at maturity, **FLH**- Fruit length at harvest, **NFP**- Number of fruit plant^{-1}, **NSF**- Number of seeds fruit^{-1}, **SI**- Seed index, **FW**- Fruit weight and **YP**- Yield plant^{-1}

*and **, significant at 5and 1 per cent level, respectively

Estimation of variances of GCA and SCA

Estimation of variance of GCA and SCA was calculated by formulae [7]

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

Where,

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

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 made by line, testers and their interactions to overall variance

Proportional contribution of line, testers and their interactions to total variance computed as per [7]

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

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

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

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

Heterosis

After conducting a variance analysis on 12 attributes listed in Table 2a, it was discovered that significant differences existed between parents and hybrids, indicating a high level of genetic diversity within the experimental group. Table 3 showcases the hybrids' heterosis in various traits, in both positive and negative directions, whereas Table 4 highlights the top five crosses. Heterosis showed significant and unfavorable effects on days to bloom halfway and days to first picking, indicating early blooming and fruit ripeness for harvesting, respectively. Farmers choose these characteristics to secure their financial stability (Table 2b). In their 2023 study, Shinde and his team discovered a notable decrease in heterosis in okra up to the 50% flowering stage. The lack of early positive outcomes in okra's typical heterosis suggested the existence of genes linked to early ripening. 5 and 17 combinations exhibited significant and adverse heterosis for early characteristics such as days to 50% blooming and days to first picking, in comparison to the standard reference (Table 3). Data from Table 4 indicates that the top five crosses displayed significant negative standard heterosis: L3 x T1 (-4.17, -8.70), L3 x T2 (-8.33, -15.94), L4 x T4 (-5.00, -7.97), L9 x T2 (-5.00, -7.25), and L9 x T3 (-4.17, -18.12). Rynjah et al. and Kerure and Pitchaimuthu both observed negative heterosis caused by varying genetic diversity in parent crosses impacting trait distribution. Nine crosses displayed significant standard heterosis with regard to plant height [10,11]. Important points of intersection are L3 x T3 (44.43), L6 x T1 (40.66), L8 x T2 (35.83), L7 x T4 (31.39), and L5 x T4 (31.17). The results were in line with the studies conducted by [3,12-14]. 29 crosses exhibited significant and favorable standard heterosis in internode count, with the most successful combinations being L3 x T3, L6 x T1, L8 x T2, L7 x T4, and L1 x T4, with values ranging from 25.00 to 32.50. Seven crosses in plant-1 showed notable and meaningful standard heterosis for branch number, with the most pronounced heterosis found in the crosses L4 x T1 (66.67), L5 x T1 (66.67), L6 x T3 (55.56), L8 x T3 (44.44), and L8 x T4 (66.67). The only hybrid crosses of L9 x T4 (6.22, 4.66) showed notable standard heterosis for fruit length during maturity and harvest. The results are consistent with studies carried out by [11,15-17]. Significant standard heterosis in fruit number per plant was observed in just five crosses: L8 x T3 (17.65), L5 x T4 (13.24), L6 x T2 (10.29), L3 x T2, and L7 x T3 (8.82). Six crosses showed notable and beneficial standard heterosis in the number of seeds per fruit, with the highest seen in the combination of L3 x T3 (3.40), then in L7 x T4, L4 x T3, L7 x T4, and L9 x T3 (1.28). Just two crossings, L9 x T3 (8.29) and L2 x T3 (3.66) exhibited considerable and advantageous standard heterosis in fruit weight. The highest yielding plant combinations are the hybrids L3 x T2 (8.28), L5 x T2 (7.47), L6 x T2 (7.42), L8 x T3 (8.46), and L9 x T3 (7.68). The seed index did not exhibit significant standard heterosis. Therefore, negative heterosis is advantageous in promoting early maturity, while positive heterosis is preferred for increasing plant height and crop yield. The results align with the studies carried out by [11,12,14,18,19].

Table 3. Estimation of standard heterosis of various characters.

SN	CROSSES	DFF	DFP	PH	NI	NB	FLM	FLH	NFP	NSF	SI	FW	YP
1	**L1 x T1**	3.33 *	-2.90 ns	19.82 **	17.50 **	0.00 ns	-14.18 **	-10.61 **	2.94 ns	-3.83 **	-12.80 ns	-5.85 **	-2.83 ns
2	**L1 x T2**	10.83 **	7.97 **	-8.13 **	10.00 **	22.22 ns	-15.67 **	-11.73 **	-8.82 **	-1.28 **	9.95 ns	-21.22 **	-27.17 **
3	**L1 x T3**	11.67 **	5.80 **	-23.80 **	2.50 **	-55.56 **	-30.85 **	-23.09 **	-29.41 **	-2.55 **	8.53 ns	-26.10 **	-49.28 **
4	**L1 x T4**	5.00 **	-1.45 ns	30.28 **	25.00 **	-11.11 ns	-21.39 **	-16.01 **	-25.00 **	1.28 **	-15.17 ns	-22.68 **	-42.22 **
5	**L2 x T1**	0.83 ns	-6.52 **	-19.78 **	-5.00 **	0.00 ns	-11.69 **	-8.75 **	-8.82 **	-3.83 **	-9.00 ns	0.98 ns	-7.62 *
6	**L2 x T2**	15.00 **	10.87 **	-11.77 **	10.00 **	33.33 **	-6.47 **	-4.84 **	-7.35 *	-1.70 **	11.85 ns	-10.24 **	-16.04 **
7	**L2 x T3**	11.67 **	4.35 *	-8.01 **	2.50 **	-33.33 **	-26.37 **	-19.74 **	-2.94 ns	-1.28 **	-7.11 ns	3.66 *	1.02 ns

https://doi.org/10.61577/jpri.2024.100002

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8	**L2 x T4**	17.50 **	8.70 **	10.12 **	17.50 **	-11.11 ns	-26.62 **	-19.93 **	-30.88 **	-2.55 **	-16.11 ns	-23.66 **	-47.41 **
9	**L3 x T1**	-4.17 **	-8.70 **	-18.09 **	10.00 **	-11.11 ns	-7.96 **	-5.96 **	1.47 ns	-0.00 ns	6.64 ns	-8.54 **	-6.46 *
10	**L3 x T2**	-8.33 **	-15.94 **	-10.67 **	-5.00 **	-22.22 ns	1.74 ns	1.30 ns	8.82 **	-2.55 **	14.69 ns	-0.24 ns	8.28 **
11	**L3 x T3**	4.17 **	-0.72 ns	44.43 **	32.50 **	-11.11 ns	-14.43 **	-10.80 **	-8.82 **	3.40 **	-15.64 ns	-13.66 **	-21.61 **
12	**L3 x T4**	0.83 ns	-5.80 **	-13.00 **	-5.00 **	11.11 ns	-11.94 **	-8.94 **	4.41 ns	-3.83 **	-4.74 ns	-3.17 *	0.66 ns
13	**L4 x T1**	5.83 **	-5.07 **	-19.31 **	2.50 **	66.67 **	-15.92 **	-11.92 **	1.47 ns	-3.83 **	-21.80 ns	-17.32 **	-16.92 **
14	**L4 x T2**	5.83 **	-1.45 ns	-30.41 **	2.50 **	-44.44 **	-18.91 **	-14.15 **	-20.59 **	-1.28 **	3.79 ns	-17.07 **	-34.06 **
15	**L4 x T3**	0.00 ns	-9.42 **	5.25 **	10.00 **	0.00 ns	-11.19 **	-8.38 **	-13.24 **	1.28 **	8.06 ns	-11.95 **	-23.63 **
16	**L4 x T4**	-5.00 **	-7.97 **	-28.80 **	-5.00 **	0.00 ns	-5.97 **	-4.47 **	-7.35 *	-2.55 **	-17.06 ns	-5.12 **	-10.56 **
17	**L5 x T1**	10.00 **	6.52 **	3.01 **	10.00 **	66.67 **	-7.96 **	-5.96 **	1.47 ns	-2.55 **	-9.00 ns	-0.00 ns	1.90 ns
18	**L5 x T2**	9.17 **	3.62 *	3.47 **	10.00 **	-22.22 ns	-19.15 **	-14.34 **	4.41 ns	2.55 **	1.42 ns	3.41 *	7.47 *
19	**L5 x T3**	12.50 **	7.25 **	-2.24 **	10.00 **	-33.33 **	-20.40 **	-15.27 **	-25.00 **	-1.28 **	21.80 ns	-22.44 **	- 42.31 **
20	**L5 x T4**	-2.50 ns	-16.67 **	31.17 **	17.50 **	-11.11 ns	1.00 ns	0.74 ns	13.24 **	-1.28 **	0.47 ns	-8.29 **	2.62 ns
21	**L6 x T1**	5.83 **	-14.49 **	40.66 **	32.50 **	-33.33 **	-11.44 **	-8.57 **	-2.94 ns	-0.00 ns	-7.11 ns	-11.71 **	- 13.84 **
22	**L6 x T2**	4.17 **	-7.25 **	-5.17 **	10.00 **	0.00 ns	-3.98 **	-2.98 **	10.29 **	-1.28 **	14.22 ns	-2.44 ns	7.42 *
23	**L6 x T3**	4.17 **	-4.35 *	-22.15 **	2.50 **	55.56 **	-1.74 ns	-1.30 ns	-7.35 *	-5.11 **	18.96 ns	-14.39 **	- 20.36 **
24	**L6 x T4**	9.17 **	2.90 ns	7.79 **	17.50 **	-44.44 **	-16.67 **	-12.48 **	-17.65 **	-2.55 **	-9.48 ns	-20.98 **	- 35.90 **
25	**L7 x T1**	0.83 ns	-3.62 *	-24.57 **	0.00 ns	-22.22 ns	-14.43 **	-10.80 **	-13.24 **	-2.55 **	-4.27 ns	-17.56 **	- 28.38 **
26	**L7 x T2**	0.83 ns	-11.59 **	-3.18 **	10.00 **	11.11 ns	-3.98 **	-2.98 **	2.94 ns	-1.28 **	12.80 ns	-8.78 **	- 6.68 *
27	**L7 x T3**	10.00 **	6.52 **	-19.99 **	2.50 **	22.22 ns	0.00 ns	0.00 ns	8.82 **	-3.83 **	18.48 ns	-11.71 **	- 4.40 ns
28	**L7 x T4**	10.00 **	7.97 **	31.39 **	25.00 **	-22.22 ns	-20.65 **	-15.46 **	1.47 ns	1.28 **	-6.64 ns	-7.32 **	- 5.02 ns
29	**L8 x T1**	6.67 **	-0.72 ns	-26.85 **	-5.00 **	-22.22 ns	-16.92 **	-12.66 **	-14.71 **	-0.00 ns	-6.16 ns	-22.68 **	- 35.16 **
30	**L8 x T2**	2.50 ns	-7.25 **	35.83 **	32.50 **	-33.33 **	-6.97 **	-5.21 **	7.35 *	-2.55 **	-9.00 ns	-8.05 **	- 1.99 ns
31	**L8 x T3**	5.83 **	-4.35 *	-29.06 **	-5.00 **	44.44 **	-11.69 **	-8.75 **	17.65 **	2.55 **	19.43 ns	-7.56 **	8.46 **
32	**L8 x T4**	6.67 **	0.00 ns	-19.31 **	2.50 **	66.67 **	-12.69 **	-9.50 **	1.47 ns	-3.83 **	-3.79 ns	-14.15 **	- 13.44 **
33	**L9 x T1**	5.00 **	-5.80 **	-13.26 **	2.50 **	-33.33 **	-16.17 **	-12.10 **	-16.18 **	-3.83 **	-0.47 ns	-17.80 **	- 31.31 **
34	**L9 x T2**	-5.00 **	-7.25 **	5.25 **	10.00 **	0.00 ns	-6.97 **	-5.21 **	-7.35 *	-1.28 **	-11.37 ns	-18.54 **	- 23.93 **
35	**L9 x T3**	-4.17 **	-18.12 **	-28.80 **	-5.00 **	0.00 ns	1.24 ns	0.93 ns	-1.47 ns	1.28 **	15.17 ns	8.29 **	7.68 *
36	**L9 x T4**	8.33 **	1.45 ns	3.01 **	10.00 **	44.44 **	6.22 **	4.66 **	5.88 ns	-2.55 **	15.64 ns	-3.90 **	2.28 ns
	SE± (sca)	0.6	0.77	0.5	0.11	0.35	0.14	0.14	0.73	0.17	0.88	0.19	9.09

Table 2b. Analysis of variance of Line x Tester for combing ability.

S. NO.	CHARACTERS	CROSSES	S. NO.	CHARACTERS	CROSSES
1	**Days to 50% Flowering**	L3 x T1 L3 x T2 L4 x T4 L9 x T2 L9 x T3	7	**Fruit Length (Harvest)**	L9 x T4 - - - -
2	**Days to First Picking**	L3 x T1 L3 x T2 L4 x T4 L9 x T2 L9 x T3	8	**Number of Fruits Plant^{-1}**	L8 x T3 L5 x T4 L6 x T2 L3 x T2 L7 x T3

https://doi.org/10.61577/jpri.2024.100002

3	**Plant Height**	L3 x T3	9	**Number of Seeds Fruit^{-1}**	L3 x T3
		L6 x T1			L7 x T4
		L8 x T2			L4 x T3
		L7 x T4			L7 x T4
		L5 x T4			L9 x T3
4	**Number of Internodes**	L3 x T3	10	**Seed Index**	-
		L6 x T1			-
		L8 x T2			-
		L7 x T4			-
		L1 x T4			-
5	**Number of Branches**	L4 x T1	11	**Fruit Weight**	L9 x T3
		L5 x T1			L2 x T3
		L6 x T3			-
		L8 x T3			-
		L8 x T4			-
6	**Fruit Length (Maturity)**	L9 x T4	12	**Yield Plant^{-1}**	L3 x T2
		-			L5 x T2
		-			L6 x T2
		-			L8 x T3
		-			L9 x T3

Overall and individual combining ability

ANOVA analysis online by tester for combining ability (Table 2b) showed notable variations among crosses for characteristics like days to hit 50% flowering, days to initial harvest, plant height, internode count, fruit count per plant, seed count per fruit, and plant yield. Understanding how to mix traits can help in selecting the best parental options and specific combinations to achieve different breeding goals. Line x tester analysis was used to analyze the data from the crosses and parental strains. Substantial differences were noted in all characteristics, including those arising from hybrids, varieties, parental lines, and line x testers. The genetic and specific combining abilities of 12 characteristics were evaluated using a L x T design with 9 rows and 4 testers. Tables 5 and 6 display the findings regarding early maturity, productivity, and traits that contribute to productivity, encompassing both general and SCA effects.

Table 5. Estimates of general combining ability (GCA) of lines and testers in for twelve characters in okra.

SN	CROSSES	DFF	DFP	PH	NI	NB	FLM	FLH	NFP	NSF	SI	FW	YP
	LINES												
1	L1	1.14 **	2.28 **	6.09 **	0.68 **	-0.31 *	-1.18 **	-1.18 **	-2.31 **	-0.09 ns	-0.20 ns	-1.12 **	49.33 **
2	L2	2.56 **	3.19 **	3.28 **	-0.32 **	-0.06 ns	-0.82 **	-0.82 **	-1.73 **	-0.68 **	-0.39 ns	0.48 **	-9.45 **
3	L3	-2.69 **	-2.39 **	3.04 **	-0.07 **	-0.22 ns	0.48 **	0.48 **	1.44 **	0.57 **	-0.01 ns	0.60 **	30.02 **
4	L4	-1.28 **	-1.56 **	11.91 **	-0.82 **	0.19 ns	-0.17 **	-0.17 **	-1.15 **	-0.09 ns	-0.50 ns	-0.28 **	21.17 **
5	L5	0.97 **	1.28 **	9.48 **	0.43 **	0.03 ns	0.01 ns	0.01 ns	0.77 **	0.66 **	0.23 ns	0.54 **	21.35 **
6	L6	0.39 ns	-1.47 **	6.67 **	0.93 **	-0.14 ns	0.43 **	0.43 **	0.10 ns	-0.59 **	0.26 ns	-0.22 **	-3.73 ns
7	L7	0.22 ns	1.11 **	0.71 **	0.09 **	-0.06 ns	0.26 **	0.26 **	1.10 **	-0.09 ns	0.33 ns	-0.07 ns	10.37 **
8	L8	0.22 ns	-0.22 ns	5.24 **	-0.32 **	0.44 **	-0.05 ns	-0.05 ns	1.77 **	0.41 **	-0.02 ns	-0.32 **	12.19 **
9	L9	-1.53 **	-2.22 **	4.14 **	-0.57 **	0.11 ns	1.04 **	1.04 **	0.02 ns	-0.09 ns	0.30 ns	0.38 **	9.75 **
	TESTERS												
10	T1	-0.43 **	-0.92 **	2.59 **	-0.19 **	0.06 ns	-0.17 **	-0.17 **	-0.12 ns	-0.62 **	-0.53 *	-0.05 ns	-3.60 ns
11	T2	-0.39 **	-0.25 ns	0.34 **	0.18 **	-0.16 ns	0.37 **	0.37 **	0.84 **	0.23 **	0.35 ns	0.21 **	14.98 **
12	T3	0.54 **	0.53 **	4.87 **	-0.38 **	-0.01 ns	-0.15 **	-0.15 **	-0.45 *	0.68 **	0.66 **	0.02 ns	-4.91 *
13	T4	0.28 *	0.64 **	7.11 **	0.40 **	0.10 ns	-0.05 ns	-0.05 ns	-0.27 ns	-0.29 **	-0.47 *	-0.18 **	-6.48 **

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SE± (Lines)	**0.30**	**0.39**	**0.13**	**0.04**	**0.18**	**0.07**	**0.07**	**0.37**	**0.09**	**0.44**	**0.09**	**4.53**
CD @ 5% (Lines)	**0.59**	**0.77**	**0.25**	**0.08**	**0.35**	**0.14**	**0.14**	**0.73**	**0.17**	**0.88**	**0.19**	**8.96**
CD @ 1% (Lines)	**0.78**	**1.02**	**0.33**	**0.10**	**0.46**	**0.19**	**0.19**	**0.97**	**0.23**	**1.17**	**0.25**	**11.91**
SE± (Testers)	**0.19**	**0.26**	**0.08**	**0.03**	**0.12**	**0.05**	**0.05**	**0.24**	**0.06**	**0.30**	**0.06**	**3.02**
CD @ 5% (Testers)	**0.39**	**0.51**	**0.17**	**0.05**	**0.23**	**0.10**	**0.10**	**0.48**	**0.12**	**0.59**	**0.12**	**5.98**
CD @ 1% (Testers)	**0.52**	**0.68**	**0.22**	**0.07**	**0.31**	**0.13**	**0.13**	**0.64**	**0.15**	**0.78**	**0.17**	**7.94**

Table 6. Estimates of specific combining ability (SCA) of crosses for twelve characters in Okra.

SN	CROSSES	DFF	DFP	PH	NI	NB	FLM	FLH	NFP	NSF	SI	FW	YP
1	**L1 x T1**	-1.32 **	-1.50 **	14.62 **	0.69 **	0.27 ns	1.02 **	1.02 **	4.20 **	-1.13 **	-0.20 ns	1.84 **	89.00 **
2	**L1 x T2**	1.64 **	2.83 **	-10.32 **	-0.68 **	1.16 **	0.28 **	0.28 **	0.57 ns	0.02 ns	0.52 ns	-0.52 **	-5.04 ns
3	**L1 x T3**	1.05 *	1.06 ns	-17.44 **	-1.12 **	-1.32 **	-1.23 **	-1.23 **	-2.80 **	-1.43 **	0.11 ns	-1.00 **	-53.71 **
4	**L1 x T4**	-1.36 **	-2.39 **	13.14 **	1.10 **	-0.10 ns	-0.07 ns	-0.07 ns	-1.98 **	2.54 **	-0.43 ns	-0.33 *	-30.25 **
5	**L2 x T1**	-3.74 **	-4.08 **	-7.18 **	-1.31 **	0.02 ns	0.99 **	0.99 **	0.95 ns	-0.55 **	0.25 ns	1.18 **	34.26 **
6	**L2 x T2**	1.89 **	3.25 **	-3.82 **	0.32 **	1.24 **	1.15 **	1.15 **	0.32 ns	0.27 *	0.84 ns	-0.61 **	-10.42 ns
7	**L2 x T3**	-0.37 ns	-0.53 ns	4.36 **	-0.12 *	-0.91 **	-1.00 **	-1.00 **	2.62 **	0.16 ns	-0.80 ns	1.48 **	62.38 **
8	**L2 x T4**	2.22 **	1.36 *	6.64 **	1.10 **	-0.35 ns	-1.13 **	-1.13 **	-3.90 **	0.12 ns	-0.30 ns	-2.05 **	-86.22 **
9	**L3 x T1**	-0.49 ns	0.50 ns	-12.17 **	0.44 **	-0.15 ns	0.19 ns	0.19 ns	0.12 ns	1.20 **	0.98 ns	-0.24 ns	-1.60 ns
10	**L3 x T2**	-2.19 **	-3.50 **	-9.27 **	-1.93 **	-0.26 ns	0.95 **	0.95 **	0.82 ns	-1.65 **	0.67 ns	0.63 **	25.52 **
11	**L3 x T3**	1.88 **	2.72 **	39.31 **	3.63 **	-0.07 ns	-0.69 **	-0.69 **	-1.88 **	2.57 **	-1.77 **	-1.01 **	-47.26 **
12	**L3 x T4**	0.81 ns	0.28 ns	-17.87 **	-2.15 **	0.48 ns	-0.46 **	-0.46 **	0.94 ns	-2.13 **	0.12 ns	0.63 **	23.34 **
13	**L4 x T1**	2.09 **	1.33 *	1.81 **	0.19 **	1.77 **	-0.22 *	-0.22 *	2.70 **	-1.13 **	-0.53 ns	-0.56 **	17.15 **
14	**L4 x T2**	2.06 **	2.33 **	-9.86 **	-0.18 **	-1.34 **	-1.16 **	-1.16 **	-3.26 **	0.02 ns	0.39 ns	-0.79 **	-54.57 **
15	**L4 x T3**	-1.20 **	-2.11 **	23.42 **	1.38 **	-0.16 ns	0.39 **	0.39 **	-0.30 ns	1.57 **	0.39 ns	0.10 ns	-2.34 ns
16	**L4 x T4**	-2.94 **	-1.56 **	-15.36 **	-1.40 **	-0.27 ns	0.99 **	0.99 **	0.85 ns	-0.46 **	-0.25 ns	1.24 **	39.76 **
17	**L5 x T1**	1.51 **	3.83 **	-2.01 **	-0.06 ns	1.94 **	0.66 **	0.66 **	0.79 ns	-0.88 **	-0.36 ns	0.98 **	33.00 **
18	**L5 x T2**	1.14 **	1.83 **	-4.58 **	-0.43 **	-0.51 *	-1.38 **	-1.38 **	0.49 ns	2.27 **	-0.51 ns	1.19 **	31.68 **
19	**L5 x T3**	1.55 **	2.72 **	-3.87 **	0.13 *	-0.99 **	-1.02 **	-1.02 **	-4.88 **	-1.18 **	0.62 ns	-2.15 **	102.79 **
20	**L5 x T4**	-4.19 **	-8.39 **	10.45 **	0.35 **	-0.44 ns	1.74 **	1.74 **	3.60 **	-0.21 ns	0.25 ns	-0.02 ns	38.11 **
21	**L6 x T1**	0.43 ns	-3.08 **	30.43 **	2.44 **	-0.90 **	-0.23 *	-0.23 *	0.45 ns	2.37 **	-0.26 ns	0.14 ns	9.28 ns
22	**L6 x T2**	-0.28 ns	-0.42 ns	-8.57 **	-0.93 **	0.32 ns	0.23 *	0.23 *	2.49 **	0.52 **	0.36 ns	1.15 **	56.60 **
23	**L6 x T3**	-1.20 **	0.14 ns	-16.73 **	-1.37 **	1.84 **	1.05 **	1.05 **	-0.21 ns	-2.93 **	0.39 ns	-0.30 *	-9.64 ns
24	**L6 x T4**	1.06 *	3.36 **	-5.14 **	-0.15 **	-1.27 **	-1.05 **	-1.05 **	-2.73 **	0.04 ns	-0.48 ns	-0.99 **	-56.24 **
25	**L7 x T1**	-1.41 **	-0.67 ns	-13.52 **	-1.06 **	-0.65 *	-0.46 **	-0.46 **	-2.88 **	-0.13 ns	-0.13 ns	-0.80 **	-49.93 **
26	**L7 x T2**	-1.44 **	-5.00 **	0.37 *	-0.09 ns	0.57 *	0.40 **	0.40 **	-0.18 ns	0.02 ns	0.19 ns	0.14 ns	-1.21 ns
27	**L7 x T3**	1.30 **	2.56 **	-7.65 **	-0.54 **	0.76 **	1.46 **	1.46 **	2.45 **	-2.43 **	0.29 ns	-0.07 ns	25.75 **
28	**L7 x T4**	1.56 **	3.11 **	20.80 **	1.69 **	-0.69 **	-1.41 **	-1.41 **	0.60 ns	2.54 **	-0.35 ns	0.73 **	25.39 **
29	**L8 x T1**	0.93 *	2.00 **	-10.79 **	-1.31 **	-1.15 **	-0.48 **	-0.48 **	-3.88 **	1.37 **	0.09 ns	-1.26 **	-72.78 **
30	**L8 x T2**	-0.78 ns	-1.67 **	35.61 **	3.32 **	-1.26 **	0.31 **	0.31 **	0.16 ns	-1.48 **	-0.99 ns	0.48 **	11.51 ns

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31	**L8 x T3**	-0.37 ns	-1.11 *	-10.25 **	-1.12 **	0.93 **	0.20 ns	0.20 ns	3.79 **	2.07 **	0.70 ns	0.74 **	63.80 **
32	**L8 x T4**	0.22 ns	0.78 ns	-14.56 **	-0.90 **	1.48 **	-0.03 ns	-0.03 ns	-0.06 ns	-1.96 **	0.20 ns	0.04 ns	-2.53 ns
33	**L9 x T1**	2.01 **	1.67 **	-1.19 **	-0.06 ns	-1.15 **	-1.47 **	-1.47 **	-2.46 **	-1.13 **	0.16 ns	-1.29 **	-58.37 **
34	**L9 x T2**	-2.03 **	0.33 ns	10.44 **	0.57 **	0.07 ns	-0.78 **	-0.78 **	-1.43 **	0.02 ns	-1.48 *	-1.65 **	-54.08 **
35	**L9 x T3**	-2.62 **	-5.44 **	-11.15 **	-0.87 **	-0.07 ns	0.84 **	0.84 **	1.20 *	1.57 **	0.08 ns	2.20 **	63.81 **
36	**L9 x T4**	2.64 **	3.44 **	1.90 **	0.35 **	1.15 **	1.41 **	1.41 **	2.69 **	-0.46 **	1.24 ns	0.74 **	48.64 **
	SE± (sca)	**0.59**	**0.78**	**0.25**	**0.08**	**0.35**	**0.14**	**0.14**	**0.73**	**0.17**	**0.89**	**0.19**	**9.05**
	CD @ 5% (sca)	**1.17**	**1.54**	**0.50**	**0.16**	**0.70**	**0.29**	**0.29**	**1.45**	**0.35**	**1.76**	**0.37**	**17.93**
	CD @ 1% (sca)	**1.56**	**2.05**	**0.67**	**0.21**	**0.93**	**0.38**	**0.38**	**1.93**	**0.46**	**2.33**	**0.50**	**23.81**

*and **, significant at 5and 1 per cent level, respectively

GCA (General combining ability)

In Line L3, a strong adverse effect of GCA is seen on the days required for 50% flowering and first picking, while the biggest beneficial impact is noted on plant height, fruit length, fruit quantity per plant, seed quantity per fruit, fruit weight, and plant yield. Hence, L3 is regarded as the top combiner for these traits in general. L9 showed a significant negative impact on days to 50% blooming (-1.53) and days to first picking (-2.22) with GCA effects. However, characteristics like fruit length at maturity and harvest (1.04), fruit weight (0.38), and yield plant-1 (9.75) showed strong positive effects in terms of GCA.

Tester T2 showed a large detrimental impact on genetic combining ability up to 50% blooming, with a value of -0.39. Nonetheless, the identical genetic composition exhibited considerable favorable effects on various traits like plant height, internode number, fruit length at maturity and harvest, number of fruits per plant, seeds per fruit, fruit weight, and plant yield. GCA resulted in noticeable adverse impacts on characteristics like time to 50% blooming (-0.43) and time to first picking (-0.92) as observed in T1. Likewise, T3 significantly influenced both the number of seeds per fruit (0.68) and seed index (0.66) attributes. Lines L1, L3, L4, L5, L7, L8, and L9 showed notable genetic combining ability effects on trait yield, while no effects were noticed for tester T2. Positive and notable results in GCA were attained by [20-24].

SCA (Specific combining ability)

One of the crosses, cross L1 x T1, had notable negative impacts on various characteristics such as flowering time, time to first harvest, height of the plant, number of internodes, amount of fruit, weight of fruit, and overall plant yield. The combination of L1 and T4 had noticeable negative effects on the time it took for plants to reach 50% flowering and the time of the first harvest while showing substantial advantages for plant height and the quantity of internodes. Even though it had negative impacts on blooming and harvesting time, the hybrid L2 x T1 had a noteworthy positive impact on fruit weight and yield per plant. The hybrid L3 x T2 had noticeable adverse effects on days until 50% flowering (-2.19) and days until first picking (-3.50) but had favorable effects on fruit length (0.95). Nevertheless, the hybrid L4 x T4 showed significant negative effects on SCA for days to 50% flowering (-2.94) and days to first picking (-1.56). The identical hybrid exhibited noteworthy and advantageous impacts on the length of fruit (0.99), weight of fruit (1.24), and yield per plant (39.76) with SCA. The combination of L5 x T1 had significant and positive effects on the characteristics of branches per plant (1.94), fruit length (0.66), fruit weight (0.98), and plant yield (33.00). The hybrid L5 x T4 resulted in significant reductions in the time required to reach 50% flowering (-4.19 days) and the first harvest (-8.39 days). The SCA had a beneficial effect on plant height (10.45), number of internodes (0.35), and yield per plant (38.11). The hybrid L7 x T3 showed significant GCA effects, leading to an increase in branches per plant (0.76), fruit length (1.46), and yield per plant (25.75). Likewise, the hybrid L9 x T3 exhibited significant decreases in days to 50% flowering (-2.62) and days to first picking (-5.44) due to SCA. Nevertheless, SCA resulted in notable and beneficial effects on fruit weight (2.20) and yield per plant (63.81). The hybrid L9 x T4 showed strong and beneficial effects on characteristics such as plant height (1.90), internode count (0.35), number of branches per plant (1.15), fruit length (1.41), fruit weight (0.74), and plant yield (48.64) through SCA. Similar findings were also documented by [3,14,16,25-27].

GA (Gene action)

Table 7 displays the GCA and SCA variances calculations (σ 2GCA and σ2SCA) along with gene action. In cases where σ2gca is less than σ2sca, the ratio of GCA to SCA (σ2GCA: σ2SCA) will be below one, as shown in the Table 8. As a result, the gene expression of each characteristic analyzed did not add up.

Yield is regulated by a complex system of genes. Breeders must comprehend gene function to choose optimal breeding methods and enhance crop production and yield-related traits. Three types of gene actions, namely additive, dominant, and epistasis, influence character expression. When enhancing crops and selecting techniques depend greatly on the functionality of extra genes. On the other hand, the interplay among genes in dominance and epistasis includes both allelic and non-allelic elements. In these situations, developing hybrid varieties or utilizing heterosis can be beneficial. Therefore, breeders can select the most effective breeding techniques by gaining knowledge about the role of genes. Previous studies by Nimbalkar et al., Reddy and Sridevi, Pithiya et al., and Patel et al. indicated comparable findings regarding the significance of gene action (non-additive) in transmitting essential yield and yield-related characteristics, highlighting the possibility of utilizing heterosis [28-30].

https://doi.org/10.61577/jpri.2024.100002

Table 7. Contribution of Lines and Tester.

CHARACTERS	LINE	TESTER	LINE x TESTER	Var. GCA	Var. SCA	Gene Action
Days to 50% Flowering	39.81	3.09	57.10	0.05	4.66	Non-Additive
Days to First Picking	30.46	3.25	66.30	0.02	11.87	Non-Additive
Plant Height	14.80	7.14	78.06	2.17	332.42	Non-Additive
Number of Internodes	14.42	4.42	81.16	0.02	2.56	Non-Additive
Number of Branches	4.83	1.03	94.14	0.02	1.29	Non-Additive
Fruit Length (Commercial Maturity)	31.31	3.69	65.00	0.00	1.26	Non-Additive
Fruit Length (Final Maturity)	31.31	3.69	65.00	0.00	1.26	Non-Additive
Number of Fruits per Plant	25.19	3.41	71.41	0.02	7.61	Non-Additive
Number of Seeds per Fruit	7.40	9.20	83.40	0.03	3.31	Non-Additive
Seed index	11.45	35.54	53.01	0.01	0.20	Non-Additive
Fruit Weight	19.72	1.45	78.83	0.01	1.65	Non-Additive
Yield per Plant	18.61	2.71	78.69	22.93	3266.48	Non-Additive

Table 8. Best General and Specific Combiners for twelve characters in Line x Tester analysis of okra.

S. No.	Characters	GCA	SCA
1	Days to 50% Flowering	L3	L5 x T4
2	Days to First Picking	L3	L5 x T4
3	Plant Height	L4	L8 x T2
4	Number of Internodes	L6	L3 x T3
5	Number of Branches	L8	L6 x T3
6	Fruit Length (Maturity)	L3	L5 x T4
7	Fruit Length (Harvest)	L9	L5 x T4
8	Number of Fruits per Plant	L8	L1 x T1
9	Number of Seeds per Fruit	T3	L1 x T4
10	Seed Index	T3	-
11	Fruit Weight	L3	L9 x T3
12	Yield per Plant	L1	L5 x T3

Conclusions

The main objective of the present study is to grasp the significance of heterosis in enhancing crop yield. Hybrids L3 crossed with T2 (8.28), L8 crossed with T3 (8.46), and L9 crossed with T3 (7.68) displayed significant positive heterosis for crop yield. The point of intersection for L3 x T2 at (-8.33, -15.94) and L9 x T3 at (-4.17, -18.12) displayed reduced heterosis for days to 50% flowering and days to first picking when compared to the standard check, suggesting early maturity characteristics. Further testing in various locations may be needed before these hybrid vehicles are ready for commercial use. The original parents' genetic variations provided a promising chance to leverage hybrid vigor in okra for commercial purposes. Nevertheless, the parents L3, L2, and L9 were adept at blending genetic material. Parents had a notable effect on the time it took for plants to reach 50% blooming and the timing of the first picking, especially with regard to their overall combining ability (GCA). Point L3 is located at coordinates (-2.69, -2.39) and point T1 is located at coordinates (-0.43, -0.92). The gene mixture in Crosses L5 x T4 significantly decreased the number of days for flowering and first picking, whereas L5 x T3 led to an increase in plant yield. The genetic variance σ2GCA is less than σ2SCA, and the σ 2GCA: σ2SCA ratio is below 1, showing non-additive gene expression in all traits.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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