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COMBINING ABILITY ANALYSIS FOR YIELD AND ITS COMPONENT TRAITS IN OKRA (*Abelmoschus esculentus* L.) USING HALF DIALLEL MATING DESIGN

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ABSTRACT

Okra *[Abelmoschus esculentus* L. Moench] is an important vegetable crop widely cultivated in tropical and subtropical regions for its nutritional and economic importance. The present study was undertaken to assess combining ability for yield and its component traits using a half diallel mating design. The experiment was conducted during spring and summer 2023 at the Vegetable Research Farm, Banda University of Agriculture and Technology, Banda. Eight parental genotypes were crossed in a half diallel fashion to generate 28 F_1 hybrids. The parents and hybrids were evaluated in a randomized block design (RBD) with three replications. Various yield and yield attributing traits were recorded and analyzed for combining ability. Analysis of variance revealed significant differences among genotypes for all the traits studied, indicating the presence of substantial genetic variability. Estimates of general combining ability (GCA) and specific combining ability (SCA) indicated the involvement of both additive and non-additive gene effects in the inheritance of traits. Among the parents, IC-117090, Kashi Kranti and Kashi Satdhari were identified as good general combiners for fruit yield and associated characters. Among hybrids, IC-117090 × Parbhani Kranti, Kashi Kranti × Pusa Bhindi-5 and Kashi Satdhari × IC-117090 exhibited superior SCA effects for fruit yield per plant. The findings suggest that these parents and hybrids possess considerable potential for utilization in hybrid breeding programmes aimed at developing high yielding okra hybrids.

***Keywords* :** Combining ability, Diallel analysis, Gene action, Hybrid breeding, Okra, Yield.

Introduction

Okra (*Abelmoschus esculentus* (L.) Moench), commonly known as bhendi or lady's finger, is an important vegetable crop widely cultivated in tropical and subtropical regions of the world, particularly in India. It belongs to the family Malvaceae and is believed to have originated in tropical Africa. The crop is valued for its tender green fruits, which are consumed as a vegetable and are rich in nutrients such as carbohydrates, proteins, vitamins and minerals. Okra is grown extensively in several Indian states including Uttar Pradesh, Bihar, West Bengal, Gujarat, Karnataka and Andhra Pradesh due to its wide adaptability and economic importance. The species is an amphidiploid with a chromosome number of 2n = 130 and exhibits considerable genetic variability, which provides ample scope for crop improvement (Thamburaj and Singh 2018).

In addition to its nutritional value, okra has significant medicinal and industrial importance. The fruits are known to contain ascorbic acid, carotene and dietary fiber, while the seeds are a good source of protein and edible oil (Agbowuro *et al*. 2019, Rambabu *et al*. 2019). Fruits include in soluble fiber, which reducing the risk of colon cancer. Additionally, it can also benefit people with genitor-urinary issues (Demta *et al*. 2019). It helps treat goitre and is a great source of iodine (Purewal and Randhawa, 1947). The crop is also utilized in various traditional and modern food preparations and has applications in pharmaceutical and paper industries (Wammanda, 2007). Due to its short duration and ability to produce throughout the year under suitable conditions, okra plays an importance role in increasing farmers' income and ensuring nutritional security.

Despite its importance, the productivity of okra is often limited by the lack of high yielding and stable varieties. Therefore, the development of superior hybrids through systematic breeding approaches has become a major focus in recent years. The selection of appropriate parental lines and comprehension of the nature of gene action determining yield and its component qualities are critical to the success of any breeding program. The ideas of general combining ability (GCA) and specific combining ability (SCA) were initially introduced in regard to single corn crosses by Sprague and Tatum (1942). The effects of general combining ability helps in the selection of superior parents, while the specific combining ability helps in the selection of superior hybrids. One of the best methods for assessing parents' genetic potential and finding ideal hybrid combinations is combining ability analysis. Specific combining ability (SCA) is linked to non-additive gene action like dominance and epistasis, while general combining ability (GCA) represents additive gene effects that can be corrected through selection. The relative significance of additive and non-additive genetic variations can be ascertained through the estimation of GCA and SCA, which also helps breeders select suitable breeding techniques. Among various mating designs, the half diallel mating design is widely used as it allows efficient evaluation of genetic parameters while reducing the number of crosses, making it cost-effective and time-saving for breeders. The identification of superior parents with high GCA effects and cross combinations with high SCA effects is essential for developing high yielding hybrids in okra. Furthermore, understanding the genetic architecture of yield and its related traits provides valuable insights for planning effective breeding programmes. Although several studies have been conducted on combining ability in okra, there is still a need to evaluate diverse genotypes under specific agro-climatic conditions to identify stable and high performing hybrids. Therefore, the present investigation was undertaken to estimate the combining ability and to identify promising parents and hybrid combinations for yield and its component traits in okra using a half diallel mating design.

Materials and Methods

The experimental material for the present study consisted of eight parental genotypes of okra [*Abelmoschus esculentus* L. Moench], namely Kashi Vibhuti, Kashi Mahima, Kashi Satdhari, Kashi Kranti, IC-117090, Parbhani Kranti, Kashi Lalima and Pusa Bhindi-5, obtained from ICAR-Indian Institute of Vegetable Research (IIVR), Varanasi. A half diallel mating design excluding reciprocals was employed to develop twenty-eight F_1 hybrid combinations. The investigation was conducted at the Vegetable Research Farm, Department of Horticulture, Banda University of Agriculture and Technology, Banda, India, during the spring and summer seasons of 2023.

The experiment was laid out in a randomized block design (RBD) with three replications by adopting recommended spacing between rows and plants. The experimental field consisted of sandy loam soil having pH ranging from 5.5 to 6.0. During the spring season, the temperature ranged from 18.2°C to 26.4°C, while during the kharif season it varied between 33.8°C and 41.3°C. Recommended agronomic practices were followed to raise a healthy crop stand. Fertilizers were applied at the rate of 100:60:50 kg N:P:K per hectare through urea, single super phosphate and muriate of potash, respectively. Irrigation was provided at an interval of 2–3 days depending upon soil moisture status and prevailing environmental conditions. Weed management was carried out manually to maintain weed-free conditions throughout the crop growth period.

Observations were recorded on five randomly selected plants from each replication for sixteen quantitative traits viz., days to 50% flowering, plant height at 50% flowering, node number at first flower appearance, internodal length (cm), days to first edible fruit harvest, petiole length (cm), leaf area (cm^2), fruit length (cm), fruit tip length (cm), fruit diameter (cm), number of primary branches per plant, number of fruits per plant, average fruit weight (g), fruit yield per plant (g), fruit yield (q/ha) and total soluble solids (°Brix). A meter scale was used to measure the plant's height from the base to the tip. Based on field observations, the number of days until 50% flowering and the first harvest of edible fruit were noted. Each plant's principal branches and fruits were counted by hand. A leaf area meter was used to calculate the leaf area. Fruit diameter was measured with a vernier caliper, while fruit length, fruit tip length, and petiole length were measured with a centimeter scale. A weighing balance was used to record average fruit weight and yield, and a hand refractometer was used to measure total soluble solids.

The statistical analysis was carried out to estimate general combining ability (GCA) and specific combining ability (SCA) effects for the studied traits under half diallel mating design.

Results and Discussions

The present investigation provided a comprehensive understanding of the genetic control of yield and its component traits in okra through the analysis of variance, mean performance, general combining ability (GCA) and specific combining ability (SCA). These analyses collectively revealed the presence of substantial genetic variability and the nature of gene action governing the traits under study.

Analysis of variance

The analysis of variance for combining ability using a half diallel mating design revealed highly significant differences among genotypes for all the sixteen traits studied (Table 1). The mean sum of squares due to general combining ability (GCA) were found to be highly significant for all the characters, indicating the presence of substantial genetic variability among the parental lines.

Similarly, the mean squares due to specific combining ability (SCA) were also significant for most of the traits. However, non-significant SCA effects were observed for days to 50% flowering, plant height at 50% flowering, days to first edible fruit harvest, petiole length and fruit diameter, indicating differential expression of genetic effects among these traits. The significance of both GCA and SCA mean squares for most of the characters suggested the involvement of both additive and non-additive gene effects in the inheritance of these traits. Similar findings regarding the importance of both types of gene action in okra have also been reported by Shwetha *et al.* (2018), Tiwari *et al.* (2016).

Mean performance of parents and hybrids

The mean performance of eight parental genotypes and their twenty-eight F_1 hybrids for sixteen yield and yield contributing traits is presented in Table 2. Among the parental lines, Kashi Kranti recorded comparatively superior performance for fruit yield per plant (366.12 g) and fruit yield (203.39 q/ha), followed by Kashi Satdhari (313.35 g and 174.08 q/ha) and Kashi Mahima (318.97 g and 177.20 q/ha). In contrast, Pusa Bhindi-5 exhibited relatively lower yield performance with 223.07 g fruit yield per plant and 123.92 q/ha yield.

Among the F_1 hybrids, IC-117090 × Parbhani Kranti recorded the highest fruit yield per plant (449.62 g) and fruit yield (249.79 q/ha), followed by Kashi Satdhari × IC-117090 (467.01 g and 259.45 q/ha) and Kashi Mahima × Kashi Kranti (425.69 g and 236.49 q/ha). These hybrids demonstrated superior performance over their respective parents for yield and associated traits. For yield contributing traits, considerable variation was observed among both parents and hybrids. The number of fruits per plant ranged from 8.40 in Kashi Vibhuti × Pusa Bhindi-5 to 23.23 in Kashi Kranti × IC-117090, while average fruit weight varied from 11.88 g in Kashi Kranti × Parbhani Kranti to 27.92 g in Kashi Satdhari × IC-117090. Similarly, days to 50% flowering ranged from 37.93 days (Kashi Kranti × Pusa Bhindi-5) to 50.57 days (Kashi Vibhuti × Parbhani Kranti), indicating variability in earliness among the genotypes. Plant height at 50% flowering varied between 29.93 cm (Kashi Vibhuti) and 40.60 cm (Kashi Mahima), reflecting diversity in vegetative growth. The observed variation among parents and hybrids for different characters indicated the presence of sufficient genetic variability, which can be effectively utilized for further breeding programmes.

The analysis of variance indicated highly significant differences among genotypes for all the traits, confirming the existence of considerable genetic variability in the experimental material. The evaluation of mean performance further supported the presence of wide variability among parents and hybrids. Among the parental lines, Kashi Kranti, Kashi Satdhari and Kashi Mahima exhibited superior performance for fruit yield and its contributing traits, indicating their potential as promising genotypes. Similarly, among hybrids, crosses such as IC-117090 × Parbhani Kranti, Kashi Satdhari × IC-117090 and Kashi Mahima × Kashi Kranti showed superior performance for fruit yield per plant and yield (q/ha), demonstrating the presence of heterotic effects. Such superior performance of hybrids due to genetic interactions has also been reported earlier by Mehta *et al.* (2007).

Table 1 : Analysis of variance (mean square) for combining ability in okra for 16 characters.

Sources of Variation	GCA	SCA	Error
Degree of Freedom	7	28	70
Days to 50% flowering	49.08**	3.32	2.44
Plant height at 50% flowering	13.37**	2.42	1.9
Node no. at first flower appear	0.67**	0.79**	0.09

Internodal length (cm)	2.75**	0.27**	0.037
Days to first edible fruit harvest	49.50**	4.28	3.7
Petiole length	5.70**	0.76	0.642
Leaf area (cm^2)	733.52**	283.52**	9.4
Fruit length (cm)	1.19**	0.52*	0.3
Fruit tip length	0.09**	0.00**	0
Fruit diameter (cm)	0.01**	0	0
No. of primary branches	0.19**	0.15**	0.04
No. of fruit per plant	18.43**	7.96**	0.77
Average fruit weight (gm)	22.29**	12.00*	1.01
Total yield per plant (gm)	13426.36**	6248.12 **	400.43
Fruit yield (q/ha)	4143.94**	1928.50*	123.59
TSS	0.02**	0.03**	0

Table 2 : Mean performance of parents and their F_1,s for 16 characters in okra

Genotypes	Days to 50% flowering	Plant height at 50% flowering	Node no. at first flower appear	Internodal length (cm)	Days to first edible fruit harvest	Petiole length	Leaf area (cm2)	Fruit length (cm)	Fruit tip length	Fruit diameter (cm)	No. of primary branches	No. of fruit per plant	Average fruit weight (gm)	Total yield per plant (gm)	Fruit yield (q/ha)	TSS
Kashi Vibhuti	49.47	29.93	3.93	4.07	55.27	10.98	93.96	8.87	1.28	1.49	2.37	15.13	17.57	264.47	146.93	2.45
Kashi Mahima	45.16	40.60	4.20	6.80	53.61	12.31	105.25	9.39	1.52	1.39	2.80	16.53	19.26	318.97	177.20	2.39
Kashi Satdhari	48.57	39.73	4.67	5.53	55.80	14.80	126.93	10.33	1.80	1.44	2.53	16.73	18.25	313.35	174.08	2.55
Kashi Kranti	41.77	36.73	3.87	4.33	47.00	13.00	95.67	9.29	1.75	1.43	3.23	20.53	17.96	366.12	203.39	2.60
IC-117090	44.27	36.53	3.88	4.73	50.20	12.10	71.55	11.37	1.56	1.55	2.27	14.00	21.57	299.18	166.20	2.57
Parbhani Kranti	51.47	39.67	4.13	4.87	57.33	14.03	119.94	9.93	2.03	1.39	3.40	13.80	20.29	280.66	155.91	2.61
Kashi Lalima	46.80	36.80	4.15	3.53	53.00	13.90	97.31	9.94	1.64	1.45	2.50	12.26	19.28	237.50	131.94	2.22
Pusa Bhindi-5	43.27	35.93	4.04	3.47	49.60	10.90	95.42	9.05	1.41	1.43	2.53	13.20	16.84	223.07	123.92	2.19
Kashi Vibhuti x Kashi Mahima	47.47	35.73	3.80	5.27	53.00	12.03	99.33	10.58	1.52	1.53	2.93	16.80	18.22	304.53	169.17	2.35
Kashi Vibhuti x Kashi Satdhari	48.90	35.27	3.60	4.63	54.40	12.93	114.72	9.73	1.50	1.48	2.73	16.86	19.51	334.47	185.81	2.32
Kashi Vibhuti x Kashi Kranti	45.67	34.67	3.60	4.00	52.47	12.03	88.97	11.32	1.49	1.49	2.30	15.60	18.59	287.52	159.73	2.21
Kashi Vibhuti x IC-117090	47.00	34.60	3.60	4.23	52.33	11.10	66.72	12.22	1.61	1.53	3.03	16.93	16.97	290.58	161.43	2.24
K. Vibhuti x Parbhani Kranti	50.57	35.53	3.87	4.30	56.13	12.10	119.07	10.05	1.53	1.57	2.00	13.20	24.91	327.47	181.92	2.47
Kashi Vibhuti x Kashi Lalima	47.53	34.40	3.93	3.63	54.33	12.17	70.15	9.67	1.51	1.45	2.20	15.66	16.04	253.15	140.63	2.33
Kashi Vibhuti x Pusa Bhindi-5	46.43	34.47	6.40	3.60	52.73	11.00	100.80	10.33	1.62	1.63	2.67	8.40	19.97	166.79	92.65	2.51
K. Mahima x Kashi Satdhari	44.00	37.40	5.60	6.17	50.27	14.00	63.82	11.74	1.69	1.43	2.97	15.60	23.90	372.95	207.19	2.19
Kashi Mahima x Kashi Kranti	40.43	34.73	3.43	3.04	46.00	9.35	73.07	10.79	1.81	1.54	2.53	21.42	19.81	425.69	236.49	2.19
Kashi Mahima x IC-117090	44.00	39.93	4.93	5.77	50.80	12.03	58.89	10.84	1.47	1.54	3.53	15.66	22.67	353.92	196.61	2.62
K. Mahima x Parbhani Kranti	48.43	38.53	5.20	5.83	53.44	13.03	87.90	10.15	1.83	1.39	3.20	16.93	21.33	360.28	200.15	2.21
Kashi Mahima x Kashi Lalima	38.37	32.53	3.20	3.58	45.78	10.40	82.81	9.85	1.53	1.44	2.37	15.44	19.05	293.08	162.82	2.20
K. Mahima x Pusa Bhindi-5	42.83	36.80	4.73	5.10	50.03	11.93	73.87	9.52	1.44	1.52	2.73	10.60	13.30	140.90	78.27	2.59
Kashi Satdhari x Kashi Kranti	40.97	35.40	4.20	4.90	48.57	14.00	84.13	11.12	1.74	1.61	2.93	18.00	22.21	404.11	224.50	2.17
Kashi Satdhari x IC-117090	45.77	37.60	4.60	5.13	52.33	13.10	80.85	10.40	1.63	1.62	2.23	16.80	27.92	467.01	259.45	2.26
K. Satdhari x Parbhani Kranti	50.17	37.53	4.80	5.20	57.60	14.03	112.18	9.97	1.83	1.49	3.27	15.60	27.27	427.75	237.63	2.12

Kashi Satdhari x Kashi Lalima	46.47	37.27	5.20	4.50	52.67	13.90	114.35	11.14	1.71	1.52	2.23	9.60	15.90	153.43	85.23	2.55
Kashi Satdhari x Pusa bhindi5	45.53	35.53	6.00	4.50	53.00	12.93	85	9.94	1.62	1.47	2.73	15.66	12.67	200.68	111.48	2.41
Kashi Kranti x IC-117090	39.87	34.13	3.71	3.16	44.26	9.60	82.02	10.15	1.59	1.70	3.13	23.23	23.44	310.76	172.64	2.68
Kashi Kranti x Parbhani Kranti	46.90	34.00	5.60	4.60	55.07	14.00	56.99	9.56	1.82	1.54	2.73	9.70	11.88	115.26	64.03	2.67
Kashi Kranti x Kashi Lalima	40.10	34.20	5.87	3.93	47.40	13.03	62.77	9.84	1.67	1.50	3.07	14.40	20.79	301.60	167.55	2.75
Kashi Kranti x Pusa bhindi5	37.93	34.67	2.84	3.28	43.72	11.33	79.42	8.79	1.55	1.55	3.40	15.66	20.15	362.02	201.12	2.47
IC-117090 x Parbhani Kranti	47.90	36.47	6.13	4.80	54.80	13.00	88.04	11.14	1.80	1.51	2.33	18	24.65	449.62	249.79	2.40
IC-117090 x Kashi Lalima	40.24	36.27	3.63	4.13	45.59	12.49	65.20	9.70	1.54	1.50	2.73	16.41	23.79	396.96	220.53	2.33
IC-117090 x Pusabhindi-5	44.13	36.47	5.20	4.10	50.27	11.10	67.86	9.82	1.50	1.51	3.13	9.66	20.90	202.81	112.67	2.48
P. Kranti x Kashi Lalima	48.50	38.33	4.47	4.20	54.60	13.90	60.67	9.18	1.79	1.39	2.20	14.60	19.44	283.88	157.71	2.32
P. Kranti x Pusa bhindi 5	47.13	37.13	4.60	4.17	53.60	12.03	105.77	9.95	1.69	1.36	2.60	13.53	14.47	197.58	109.76	2.81
Kashi Lalima x Pusa Bhindi5	45.47	35.13	4.60	3.50	51.40	11.93	96.32	9.35	1.50	1.39	3.07	15.60	17.19	268.87	149.37	2.45
Kashi Chaman (check)	47.40	36.33	5.33	4.60	55.47	14.00	100.31	10.75	1.80	1.42	3.03	14.46	18.83	265.7	147.57	2.56
Parents mean	46.34	36.99	4.10	4.66	52.72	12.75	100.75	9.77	1.62	1.44	2.70	15.27	18.87	287.91	159.94	2.48
Cross (C) means	44.95	35.88	4.54	4.40	51.30	12.30	83.63	10.24	1.62	1.50	2.74	15.19	19.89	301.91	167.72	2.40
P+C mean	45.64	36.43	4.32	4.53	52.01	12.52	92.19	10.005	1.62	1.47	2.72	15.23	19.38	294.91	163.83	2.44
CV	5.98	6.62	11.76	7.51	6.46	11.19	6.07	9.47	3.48	7.00	13.18	10.03	8.87	11.60	11.60	3.34
SE	1.56	1.38	0.30	0.19	1.92	0.80	3.07	0.55	0.03	0.06	0.21	0.88	1.01	20.01	11.12	0.05
CD@5%	4.41	3.89	0.85	0.55	5.43	2.26	8.65	1.56	0.09	0.17	0.59	2.49	2.84	56.44	31.36	0.13
Range Lowest	37.93	29.93	2.84	3.04	43.72	9.35	56.99	8.79	1.28	1.36	2.00	8.40	11.88	115.26	64.03	2.12
Range Highest	51.47	40.60	6.40	6.80	57.60	14.80	126.93	12.22	2.02	1.70	3.53	23.23	27.92	467.01	259.45	2.81

Estimation of combining ability

Combining ability analysis helps in understanding how different genes influence the expression of various traits and assists breeders in selecting suitable parents and crosses for crop improvement. In this study, the General Combining Ability (GCA) effects of the parent genotypes and the Specific Combining Ability (SCA) effects of the hybrids were evaluated for sixteen different traits. The results provide useful information about the genetic contribution of parents and crosses to trait performance and are discussed in detail below.

General combining ability (GCA) effects

The estimates of general combining ability (GCA) effects for various growth and yield traits are presented in Table 3. The GCA analysis revealed considerable variation among the parents for all the characters studied, indicating differential genetic potential of the genotypes and the presence of additive gene effects governing these traits. Such variability among parents is essential for effective selection in breeding programmes, as also emphasized by Nagesh *et al*. (2014), Khanpara *et al*. (2009) and Jonah *et al*. (2015).

Regarding days to 50% flowering, significant negative GCA effects, which are desirable for earliness, were observed in Kashi Kranti (−3.20) and Kashi Mahima (−1.15), identifying them as good general combiners for early flowering, whereas the remaining parents exhibited either non-significant or positive effects. The presence of negative GCA effects suggests the predominance of additive gene action for earliness, indicating that these parents can be effectively utilized in selection programmes aimed at developing early-maturing varieties. Similar findings have been reported by Nagesh *et al*. (2014), who highlighted the importance of identifying parents with desirable GCA effects for maturity traits. In relation to node number at first flower appearance, significant positive GCA effects were recorded in Kashi Mahima (1.17), Parbhani Kranti (1.17) and Kashi Satdhari (1.03), whereas Kashi Vibhuti (−0.34) and Kashi Kranti (−0.31) showed significant negative effects. Positive GCA effects for this trait indicate improved reproductive efficiency, which contributes to better yield potential. These observations are in agreement with earlier reports by Khanpara *et al*. (2009) and Jonah *et al*. (2015), who also observed the role of additive gene action in yield-contributing traits. With respect to internodal length, four parents namely Kashi Lalima (−0.56), Pusa Bhindi-5 (−0.50), Kashi Kranti (−0.46) and Kashi Vibhuti (−0.23) exhibited significant negative GCA effects, indicating their suitability for developing compact plant types. Reduced internodal length is advantageous for better plant architecture and efficient utilization of resources. The predominance of additive gene action for this trait is consistent with the findings of Khanpara *et al*. (2009). Concerning days to first edible fruit harvest, significant negative GCA effects were observed in Kashi Kranti (−3.31) and IC-117090 (−1.38), indicating their potential for early fruit harvest. Earliness in harvesting is a desirable trait for maximizing economic returns, and the significant GCA effects suggest that this trait can be effectively improved through selection. Similar observations were also reported by Nagesh *et al*. (2014).

In the case of leaf area, positive and significant GCA effects were recorded in IC-117090 (13.42 cm^2), followed by Kashi Satdhari (12.20 cm^2) and Parbhani Kranti (8.36 cm^2), suggesting their superiority for this trait. Larger leaf area contributes to higher photosynthetic efficiency and biomass accumulation, ultimately enhancing yield. These findings are supported by earlier studies (Khanpara *et al*., 2009; Jonah *et al*., 2015). Evaluation of fruit length revealed that IC-117090 (0.56) and Kashi Satdhari (0.35) were good general combiners with significant positive effects, whereas Pusa Bhindi-5 (−0.54) exhibited significant negative GCA effect. Similarly, fruit diameter was positively influenced by IC-117090 (0.06), indicating its usefulness as a good general combiner for fruit size traits. Improvement in fruit size traits through additive gene action has also been reported by Jonah *et al*. (2015). Assessment of number of primary branches per plant indicated that Kashi Kranti (0.19) exhibited significant positive GCA effect and was identified as the best general combiner, whereas Kashi Vibhuti (−0.21) and Kashi Lalima (−0.18) showed significant negative effects. Increased branching enhances the number of fruit-bearing sites and contributes directly to yield improvement. Similar trends were reported by Khanpara *et al*. (2009). In terms of number of fruits per plant, significant positive GCA effects were observed in Kashi Kranti (2.21), Kashi Mahima (0.86) and IC-117090 (0.78), indicating their superiority as general combiners. In contrast, Pusa Bhindi-5 (−2.14), Kashi Lalima (−1.07) and Parbhani Kranti (−0.78) showed significant negative effects. Since number of fruits per plant is a major yield component, these results highlight the importance of additive gene effects in determining yield potential, as also reported by Jonah *et al*. (2015). With respect to average fruit weight, IC-117090 (2.65), Kashi Satdhari (0.89) and Parbhani Kranti (0.75) exhibited significant positive GCA effects and were identified as good general combiners, whereas Pusa Bhindi-5 (−2.46), Kashi Vibhuti (−0.77) and Kashi Lalima (−0.62) recorded significant negative effects. Improvement in fruit weight through additive gene action has been emphasized in earlier studies (Khanpara *et al*., 2009; Jonah *et al*., 2015). Focusing on fruit yield per plant, significant positive GCA effects were observed in IC-117090 (38.08), Kashi Satdhari (29.79), Kashi Kranti (24.99) and Kashi Mahima (20.00), indicating their potential as superior general combiners for yield. Similarly, fruit yield (q/ha) was significantly influenced by the same parents, namely IC-117090 (21.15), Kashi Satdhari (16.55), Kashi Kranti (13.89) and Kashi Mahima (11.11). The consistency of these parents across yield traits indicates their strong additive genetic potential. These findings are in agreement with earlier reports of (11) and (12), as well as Nagesh *et al*. (2014), who emphasized the importance of selecting superior general combiners for yield improvement.

Overall, IC-117090, Kashi Satdhari, Kashi Kranti and Kashi Mahima emerged as superior general combiners for yield and its contributing traits. However, no single parent was found to be ideal for all the traits, indicating the complex and polygenic nature of yield inheritance. The results further revealed that Kashi Kranti and IC-117090 are particularly useful for earliness, while IC-117090 also exhibited superiority for yield traits, highlighting its importance in breeding programmes. These observations are in close agreement with earlier studies by Nagesh *et al*. (2014), Khanpara *et al*. (2009) and Jonah *et al*. (2015), which also emphasized the role of additive gene action in improving yield and its associated traits.

The present findings clearly demonstrate that GCA remains a powerful and reliable tool for identifying superior parental lines with high additive genetic potential. The identified parents can be effectively utilized in selection-based breeding programmes aimed at developing high-yielding, early-maturing and improved cultivars, thereby contributing significantly to crop improvement strategies.

Table 3 : The GCA of parents for plant growth and yield traits of okra

Name of parent	Daysto50% flowering	Plant height at 50% flowering (cm)	Node number at first flower appearance	Internodal length(cm)	Days to first edible fruit harvest	Petiole length(cm)	Leaf area (cm sq)	Fruit length (cm)	Fruit tip length (cm)	Fruit diameter (cm)	No. of primary branches / plant	Number of fruits per plant	Average Fruit Weight (gm)	Fruit yield per plant (gm)	Fruit yield (q/ ha)	TSS(°Brix)
Kashi Vibhuti	2.51**	-2.06**	-0.34**	-0.23**	2.13**	-0.63**	6.07**	0.04	-0.13**	0.02	-0.21**	-0.32	-0.77*	-19.58**	-10.88**	-0.04**
Kashi Mahima	1.15*	1.17**	-0.08	0.82**	-0.81	-0.42	-3.67**	0.10	-0.03**	-0.03	0.12	0.86**	-0.02	20.00**	11.11**	-0.06**
Kashi Satdhari	1.16*	1.03*	0.33**	0.60**	1.58**	1.29**	12.20**	0.35*	0.07**	0.01	-0.05	0.46	0.89**	29.79**	16.55**	-0.06**
Kashi Kranti	3.20**	-0.99*	-0.31**	-0.46**	-3.31**	-0.23	-6.82**	-0.11	0.05**	0.03	0.19**	2.21**	-0.42	24.99**	13.89**	0.06**
IC-117090	0.99*	0.34	-0.05	0.06	-1.38*	-0.50*	13.42**	0.56**	-0.04**	0.06**	0.01	0.78**	2.65**	38.08**	21.15**	0.04**
Parbhani Kranti	3.52**	1.17**	0.29**	0.27**	3.53**	0.85**	8.36**	-0.14	0.17**	-0.04*	0.05	-0.78**	0.75*	3.39	1.88	0.05**
Kashi Lalima	0.71	-0.34	-0.09	-0.56**	-0.68	0.40	-4.00**	-0.26	-0.01	-0.03	-0.18**	-1.07**	-0.62*	-26.33**	-14.63**	-0.04*
Pusa Bhindi-5	1.14*	-0.31	0.24**	-0.50**	-1.06	-0.76**	1.29	-0.54**	-0.09**	-0.02	0.07	-2.14**	-2.46**	-70.35**	-39.08**	0.04**
S.E(gi)	0.46	0.41	0.09	0.06	0.57	0.24	0.91	0.16	0.01	0.02	0.06	0.26	0.30	5.92	3.29	0.01
S.E. (gi-gj)	0.70	0.62	0.14	0.09	0.86	0.36	1.37	0.25	0.01	0.03	0.09	0.39	0.45	8.95	4.97	0.02

Estimation of specific combining ability (SCA) effects

The estimates of specific combining ability (SCA) effects for growth and yield traits are presented in Table 4. The analysis of specific combining ability (SCA) effects revealed substantial variation among the 28 F_1 hybrids for all growth and yield-related traits, clearly indicating the predominance of non-additive gene action (dominance and epistasis) in the expression of these characters. Such findings emphasize the importance of hybrid breeding for exploiting heterosis, as also reported earlier by Balakrishnan *et al*. (2009) and Weerasekera *et al*. (2008).

Regarding days to 50% flowering, six crosses exhibited significant negative SCA effects, which are desirable for earliness. The hybrid Kashi Mahima × Kashi Lalima (−5.03) recorded the highest negative effect, followed by IC-117090 × Kashi Lalima (−3.32) and Kashi Kranti × Pusa Bhindi-5 (−3.00). Negative SCA effects suggests favorable dominance interactions contributing to early flowering. Similar observations highlighting the role of non-additive gene action in earliness have been reported by Shwetha *et al*. (2012). In terms of plant height at 50% flowering, only three hybrids showed significant positive SCA effects, highest positive effect was observed in Kashi Mahima × IC-117090 (2.30), followed by Kashi Vibhuti × Kashi Kranti (1.59) and Parbhani Kranti × Kashi Lalima (1.38). Conversely, eleven crosses exhibited significant negative SCA effects, with the maximum negative effect recorded in Kashi Kranti × Pusa Bhindi-5 (-1.55), followed by Kashi Mahima × Kashi Lalima (-1.09) and Kashi Vibhuti × Kashi Satdhari (-0.84). This contrasting trend reflects the complex inheritance of plant height, where both increasing and reducing effects may be beneficial depending on breeding objectives such as lodging resistance or compact plant type, as also supported by Mehta *et al*. (2007). With respect to internodal length, six hybrids exhibited significant negative SCA effects *viz*., Kashi Mahima × Kashi Kranti (-1.78) followed by Kashi Mahima × Kashi Lalima (-1.14) and Kashi Kranti × IC-117090 (-0.91). Internodal length is associated with compact plant architecture and efficient resource utilization. The significant SCA effects observed for this trait further confirm the role of dominance gene action, which is in agreement with earlier findings by Weerasekera *et al*. (2008). Concerning days to first edible fruit harvest, five crosses exhibited significant negative SCA effects, with Kashi Mahima × Kashi Lalima (−4.35) emerging as the best combination. This indicates that specific hybrid combinations can effectively reduce the time to harvest, which is economically advantageous. Similar results were also reported by Balakrishnan *et al*. (2009), who emphasized the importance of SCA in improving earliness traits.

In relation to leaf area, eleven hybrids recorded significant positive SCA effects. The cross Kashi Satdhari × Kashi Lalima (18.72) exhibited the highest value, followed by Kashi Vibhuti × Parbhani Kranti (17.20) and Kashi Kranti × IC-117090 (14.83). Increased leaf area enhances photosynthetic capacity and contributes to higher biomass production. Such improvements through non-additive gene action have also been highlighted by Shwetha *et al*. (2012). Evaluation of fruit length revealed that Kashi Vibhuti ×

IC-117090 (1.48) had the highest positive SCA effect, followed by Kashi Vibhuti × Kashi Kranti (1.25) and Kashi Mahima × Kashi Satdhari (1.15). Similarly, fruit diameter was maximized in Kashi Vibhuti × Pusa Bhindi-5 (0.13), followed by Kashi Vibhuti × Parbhani Kranti (0.10). These traits are directly associated with market preference and consumer acceptance, and their improvement through SCA effects indicates the importance of hybrid vigor, as also observed by Mehta *et al*. (2007). An assessment of number of primary branches per plant indicated that Kashi Mahima × IC-117090 (0.67) exhibited the highest positive SCA effect, followed by Kashi Satdhari × Parbhani Kranti (0.53) and Kashi Vibhuti × IC-117090 (0.50). Increased branching enhances the number of fruit-bearing sites and ultimately contributes to yield improvement. Similar findings emphasizing the importance of branching traits in yield improvement have been reported by Shwetha *et al*. (2012). Focusing on fruit yield per plant, the most promising hybrids were IC-117090 × Parbhani Kranti (109.35), Kashi Kranti × Pusa Bhindi-5 (108.57) and Kashi Satdhari × IC-117090 (100.34), all showing highly significant positive SCA effects. The superior performance of these hybrids can be attributed to favorable dominance and epistatic interactions among the parental lines. Similar trends have been reported by Balakrishnan *et al*. (2009) and Weerasekera *et al*. (2008), who emphasized the importance of SCA in identifying superior hybrid combinations for yield improvement. The occurrence of significant SCA effects in crosses involving diverse parental combinations (high × high, high × low and low × low) further highlights the role of non-additive gene interactions. Moreover, many superior hybrids involved at least one parent with good GCA effects, suggesting that both additive and non-additive gene actions influence the expression of yield and its component traits. This observation is in agreement with Shwetha *et al*. (2012), who reported that the interaction of good general combiners often results in superior hybrids. Overall, the present findings clearly demonstrate that SCA is a reliable and effective parameter for identifying superior hybrid combinations. The hybrids IC-117090 × Parbhani Kranti, Kashi Kranti × Pusa Bhindi-5 and Kashi Satdhari × IC-117090 can be effectively utilized in breeding programmes aimed at developing high-yielding cultivars. These results are further supported by earlier studies conducted by Raghuvanshi *et al*. (2010), Hazem *et al*. (2013) and Kumar *et al*. (2013), which also emphasized the importance of non-additive gene action in crop improvement.

Table 4 : The SCA of crosses for plant growth and yield traits in okra

Crosses	Days to 50% flowering	Plant height at 50% flowering (cm)	Node number at first flower appearance	Internodal length(cm)	Days to first edible fruit harvest	Petiole length(cm)	Leaf area (cm sq)	Fruit length (cm)	Fruit tip length (cm)	Fruit diameter (cm)	primary branches per	Number of fruits per plant	Average Fruit Weight (gm)	Fruit yield per plant (gm)	Fruit yield (q/ha)	TSS(0Brix)
Kashi Vibhuti x Kashi Mahima	0.84	0.50	-0.24	0.22**	0.05	0.68*	9.50**	0.30	0.05**	0.05	0.28**	1.05**	-0.66	5.30	2.94	0.03
Kashi Vibhuti x Kashi Satdhari	-0.03	0.17	0.84**	-0.19*	-0.94	-0.13	9.01**	0.79**	0.07**	-0.04	0.25**	1.50**	-0.28	25.46**	14.14**	0.00
Kashi Vibhuti x Kashi Kranti	1.09	1.59**	-0.21	0.23**	2.02**	0.49	2.28	1.25**	0.06**	0.06**	0.42**	1.51**	0.11	-16.70*	-9.28*	0.23**
Kashi Vibhuti x IC-117090	0.22	0.20	0.46**	-0.06	-0.04	-0.17	13.37**	1.48**	0.15**	-0.04	0.50**	1.27**	4.58**	-26.72**	-14.85**	0.17**
Kashi Vibhuti x Parbhani Kranti	-0.73	0.30	0.53**	-0.19*	-1.15	-0.53	17.20**	0.01	0.14**	0.10**	0.58**	0.92**	5.26**	44.85**	24.92**	0.05**
Kashi Vibhuti x Kashi Lalima	0.46	0.68	-0.09	-0.03	1.26	-0.01	19.36**	-0.25	0.02	-0.03	-0.15	1.83**	2.24**	0.25	0.14	-0.01
Kashi Vibhuti x Pusa Bhindi-5	-0.21	0.71	2.05**	-0.13	0.04	-0.02	5.99**	0.69**	0.21**	0.13**	0.06	4.35**	3.54**	-42.09**	-23.39**	0.10**
Kashi Mahima x Kashi Satdhari	-1.27*	-0.93	0.90**	0.29**	2.13**	0.73*	32.15**	1.15**	0.03*	-0.04	0.16	0.94**	3.37**	24.35**	13.53**	0.11**
Kashi Mahima x Kashi Kranti	-0.48	1.58**	0.64**	1.78**	-1.51*	2.40**	-3.87**	0.66**	0.16**	0.04	0.52**	3.14**	0.59	81.88**	45.49**	0.23**
Kashi Mahima x IC-117090	0.88	2.30**	0.61**	0.42**	1.36	0.55	11.45**	0.05	0.09**	0.01	0.67**	1.19**	0.38	-2.97	-1.65	0.22**
Kashi Mahima x Parbhani Kranti	0.81	0.06	0.54**	0.28**	-0.90	0.20	-4.22**	0.05	0.06**	-0.04	0.29**	1.64**	0.93*	38.08**	21.16**	0.20**
Kashi Mahima x Kashi Lalima	5.03**	4.43**	1.09**	1.14**	4.35**	1.98**	3.05*	-0.13	0.05**	0.01	0.31**	0.44	0.02	0.60	0.33	0.12**
Kashi Mahima x Pusa Bhindi-5	-0.14	-0.19	0.12	0.32**	0.28	0.71*	11.18**	-0.17	0.07**	0.07**	-0.20*	3.33**	3.88**	107.56**	-59.76**	0.20**
Kashi Satdhari x Kashi Kranti	2.26**	-0.77	-0.27*	0.30**	-1.33	0.54	-8.69**	0.74**	-0.01	0.07**	0.05	0.11	2.07**	50.52**	28.07**	0.25**
Kashi Satdhari x IC-117090	0.34	0.10	-0.13	0.01	0.51	-0.09	-5.36**	0.64**	-0.03*	0.06*	0.46**	0.35	4.72**	100.34**	55.75**	0.13**
Kashi Satdhari x Parbhani Kranti	0.23	-0.80	-0.27*	-0.12	0.86	-0.51	4.19**	-0.38	0.03**	0.03	0.53**	0.70*	5.96**	95.77**	53.20**	0.28**
Kashi Satdhari x Kashi Lalima	0.75	0.45	0.51**	0.00	0.14	-0.19	18.72**	0.92**	0.03*	0.06*	0.28**	5.01**	4.03**	148.83**	-82.69**	0.24**
Kashi Satdhari x Pusa bhindi 5	0.25	-1.32*	0.98**	-0.06	0.86	-0.00	15.93**	-0.01	0.01	-0.02	-0.03	2.12**	5.42**	-57.56**	-31.98**	0.02
Kashi Kranti x IC-117090	-1.21	-1.34*	0.38**	0.91**	2.67**	2.08**	14.83**	-0.44*	0.05**	0.12**	0.20*	5.02**	1.55**	-51.12**	-28.40**	0.16**
Kashi Kranti x Parbhani Kranti	1.32*	2.31**	1.17**	0.33**	3.23**	0.97**	31.98**	-0.33	-0.03*	0.05*	0.24**	6.95**	8.12**	211.93**	117.74**	0.14**
Kashi Kranti x Kashi Lalima	-1.26*	-0.60	1.81**	0.49**	-0.23	0.46	13.84**	0.07	0.01	0.01s	0.32**	1.96**	2.16**	4.13	2.29	0.31**
Kashi Kranti x Pusa bhindi 5	3.00**	-0.16	1.55**	0.23**	3.52**	-0.09	-2.49*	0.70**	0.04**	0.03	0.40**	0.37	3.37**	108.57**	60.32**	-0.05*
IC-117090 x Parbhani Kranti	0.11	-1.17*	1.44**	0.01	1.03	0.24	5.67**	0.58**	0.04**	-0.00	0.45**	2.79**	1.58**	109.35**	60.75**	0.10**
IC-117090 x Kashi Lalima	3.32**	0.14	0.69**	0.17*	3.97**	0.19	-4.81**	0.73**	0.04**	-0.01	0.17*	1.49**	2.10**	86.41**	48.01**	0.09**
IC-117090 x Pusa bhindi-5	1.00	0.31	0.56**	0.07	1.09	-0.05	-7.44**	-0.33	0.01	-0.02	0.32**	4.19**	1.05**	-63.73**	-35.40**	-0.02
Parbhani Kranti x Kashi Lalima	0.43	1.38*	-0.19	0.03	0.13	0.24	31.12**	-0.56*	-0.01	-0.03	0.41**	1.23**	-0.36	8.01	4.45	0.11**

Parbhani Kranti x Pusa bhindi5	-0.51	0.14	0.38**	-0.07	-0.49	-0.47	8.68**	0.49*	-0.01	0.07**	0.26**	1.24**	3.48**	-34.27**	-19.04**	0.31**
Kashi Lalima x Pusa Bhindi5	2.05**	-0.34	-0.00	0.10	1.53*	-0.11	11.59**	0.02	-0.03*	-0.05*	0.43**	3.60**	0.62	66.74**	37.08**	0.04*
SD(Sii)	1.23	1.09	0.24	0.15	1.52	0.63	2.42	0.44	0.03	0.05	0.16	0.70	0.79	15.78	8.77	0.04
SD(Sij)	1.42	1.25	0.27	0.18	1.75	0.73	2.78	0.50	0.03	0.05	0.19	0.80	0.91	18.15	10.08	0.04
SD (Sii- Sjj)	1.71	1.51	0.33	0.21	2.11	0.88	3.36	0.61	0.04	0.07	0.23	0.97	1.10	21.92	12.18	0.05
SD (Sij- Sik)	2.10	1.85	0.41	0.26	2.58	1.07	4.11	0.74	0.04	0.08	0.28	1.18	1.35	26.85	14.92	0.06
SD (Sij- Skl)	1.98	1.75	0.38	0.24	2.43	1.01	3.88	0.70	0.04	0.08	0.26	1.11	1.27	25.31	14.06	0.06

Conclusion

The present investigation clearly demonstrated the existence of substantial genetic variability among the parental genotypes and their hybrids for yield and its contributing traits, indicating ample scope for genetic improvement through breeding. Among the parents, Kashi Satdhari, Kashi Kranti, and IC-117090 were identified as superior general combiners for fruit yield per plant, reflecting the importance of additive gene action in yield determination. Notably, IC-117090 emerged as the best general combiner not only for fruit yield per plant but also for fruit yield on a quintal per hectare basis, highlighting its significant breeding value. In terms of specific combining ability, the hybrids IC-117090 × Parbhani Kranti, Kashi Kranti × Pusa Bhindi-5, and Kashi Satdhari × IC-117090 exhibited the highest and most desirable SCA effects for fruit yield per plant. The superior performance of these hybrids indicates the predominance of non-additive gene action and suggests that these cross combinations possess strong heterotic potential.

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Authors' contributions

RA conducted the field experiment, analyzed the data, and prepared the manuscript. AS provided guidance and supervised the research work throughout the study. DS assisted in data analysis and manuscript preparation. HS contributed to writing, data analysis, and editing of the manuscript. PK helped in conducting the field experiment and editing the manuscript. SP assisted in editing the manuscript. All authors reviewed and approved the final version of the manuscript.

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