



OPEN Exploitation of combining ability and heterotic potential of okra under the sub-mountain region of Himalayan

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Okra (*Abelmoschus esculentus* L. Moench) is a vital vegetable crop well-known for its nutritional and economic importance, especially in tropical and subtropical regions. Studying heterosis and combining ability in okra is crucial for improving its yield, quality, and resistance to diseases and pests. Heterosis can produce offspring with superior traits, while understanding combining ability helps identify the best parental combinations for breeding programs. Since okra is often cross-pollinated, utilizing heterosis offers significant advantages. The research was conducted from 2022 to 2024 at the Experimental Farm, Department of Vegetable Science, College of Horticulture, Dr. YS Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh, India. The goal was to assess heterosis, combining ability, and gene action in okra to develop resistant cultivars with higher yields. The experimental material included an F1 population of 40 crosses derived from 10 parental lines crossed with four testers in a Line × Tester design during first week of May, 2022. These were evaluated over two years, the first week of June 2023 and 2024, along with a standard check variety, Punjab-8. Pooled data from both years were analyzed for 14 horticultural traits. The cross combinations showed higher heterotic estimates compared to heterobeltosis and standard heterosis for traits such as fruit weight and fruit yield per plant. Significant GCA effects for pod yield per plant were observed in parental lines including Kashi Pragati (40. 40.03), Kashi Satdhari (24. 37), Punjab Suhabani (14. 76), and COHF N- 9 (7. 49). Among the cross combinations for fruit yield per plant, Kashi Satdhari × Punjab Suhabani (66. 96), Kashi Pragati × Palam Komal (55. 69), COHF N- 2 × Kashi Chaman (29. 15), UHF- Okra- 4 × Varsha Uphar (25. 36), COHF N- 11 × Varsha Uphar (25. 25.35), COHF N- 1 × Palam Komal (21. 42), COHF N- 1 × Kashi Chaman (21. 22), and UHF- Okra- 2 × Punjab Suhabani (18. 18.70) showed superior and significant SCA effects. Identifying these parent lines and their hybrid combinations based on their combining ability can be important for developing high-yielding okra hybrids. Future research involving multi-location trials could further evaluate these parental lines and hybrids to replace current okra cultivars (both hybrids and varieties). Improving okra cultivars with higher yields and better quality could increase farmers' profits, enhance food security and meet consumer demands.

Keywords Combining ability, Gene action, Heterobeltosis, Crosses, Line × Tester mating fashion

Abelmoschus esculentus (L.) Moench, commonly known as okra, has chromosome number $2n=2x=130$ is a widely cultivated vegetable that thrives in both summer and monsoon seasons. Its ease of cultivation, consistent

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yield, potential for year-round export, higher nutritional value, adaptability to diverse moisture conditions, strong resistance to pests and diseases have made it one of the most popular vegetable crops in tropical regions^{1,2}. Globally, India holds number one position in both the cultivation area and production of the okra contributing around 72%, hence it is cultivated in 554 thousand hectares of area having production of 7289 thousand metric tons annually with a productivity of 13.15 metric tons per hectare³. Okra is widely recognized for its tender green fruits, which are not only enjoyed when cooked but also preserved and consumed in various ways both nationally and globally⁴. Though multipurpose in its uses, okra is primarily consumed for its tender fruits, which are rich in vitamins (A, B, C, K), proteins (in seed), minerals, and iodine—a valuable nutrient for treating goitre^{5,6}.

Heterosis, defined as the superior performance of F1 crosses over both parents, has been beneficial in overcoming yield limitations and boosting productivity growth^{7,8}. The success of any breeding program depends on selecting superior parents, which requires a thorough assessment of their combining ability⁹. Combining ability is a key genetic tool used to identify superior genotypes based on their performance across multiple crosses. General combining ability (GCA) estimates reflect additive genetic effects, aiding in the selection of parents with stable and favorable traits, while specific combining ability (SCA) estimates capture non-additive effects, enabling the identification of particularly advantageous hybrid combinations⁹. Genetically diverse okra cultivars can be crossed to take advantage of complementary traits, producing hybrids with improved growth, higher fruit production, and greater overall yield potential¹⁰. By enabling more accurate predictions of hybrid performance, research on heterotic potential and combining ability accelerates breeding programs and helps produce superior cultivars. These superior cultivars not only increase farmers' productivity but also reduce production costs through proper resource utilization. Such hybrids meet all quality standards and make okra more competitive in both local and international markets.

Okra, despite its significant potential and widespread consumption in the country, is often unnoticed due to a lack of high-yielding varieties. The overall yield of open-pollinated okra cultivars seems to have decreased due to erosion of genetic diversity and limited varietal improvement over time. Additionally, the narrow genetic base resulting from repeated inbreeding has reduced the plant's ability to adapt to changing environmental conditions. Moreover, inadequate investment in breeding techniques and limited farmer access to improved germplasm have slowed down progress in improving the genetic quality of traditional okra varieties. To address these yield challenges, implementing a breeding strategy focused on hybridization would be advantageous¹¹. Furthermore, the exploitation of heterosis, the knowledge of genetic basis of diverse characters and the enhancement of quality attributes like the improvement of the nutritional value (including higher amount of vitamins, minerals & antioxidants), texture, as well as the shelf-life, constitute prime importance within the improvement of crop¹². Present cultivars might not steadily meet with consumer preferences or market expectations, thereby impacting their marketability as well as profitability.

The efficacy of the biometric design applied is therefore essential to the evaluation of parents and their combining ability. Among several methods proposed, line × tester mating fashion¹³ has been predominately preferred as an ideal design for assessing the combining ability effects (*i.e.* GCA and SCA) and variances¹⁴. The results of this research will enhance the knowledge of improvement of okra by offering insights into successful breeding methods, identifying superior parental combinations and ensuring breeding goals align with market demands. The present study was aimed to determine the heterosis and most effective general combining genotypes that are advantageous in prospective breeding initiatives, in addition to identification of specific combiners aimed at the advancement of high-yielding and quality hybrids with following objectives:

1. To evaluate the mean performance, extent and direction of heterosis for different horticultural traits.
2. To assess the combining ability of parental lines and testers for horticultural traits.

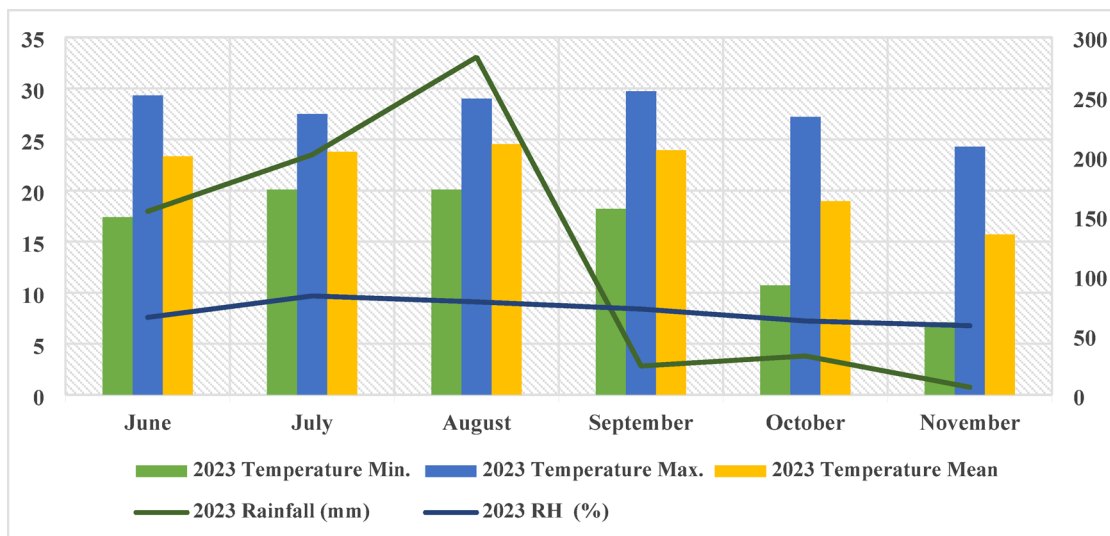
Methods

Location

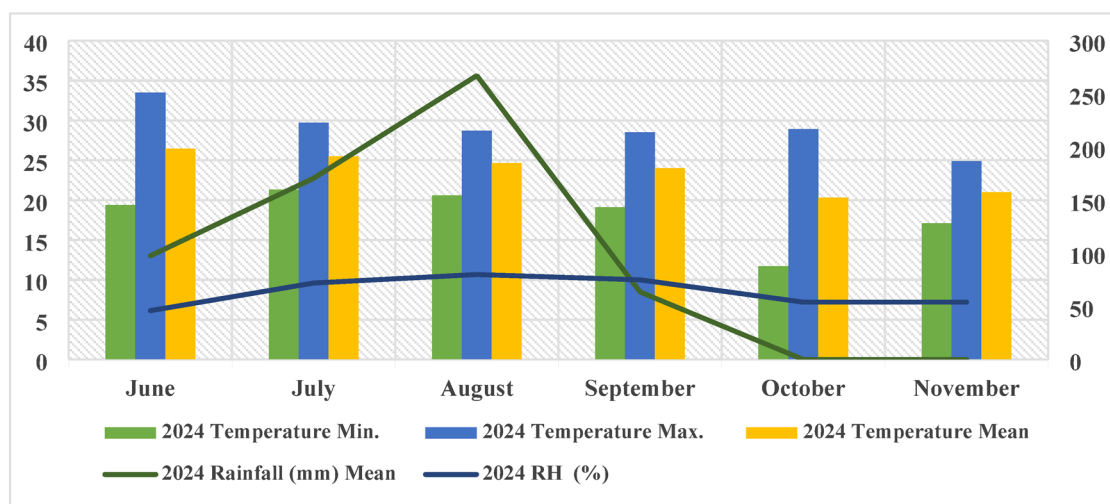
The present research was conducted at the Vegetable Research Farm under the Department of Vegetable Science, College of Horticulture, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, located in Nauni, Solan, Himachal Pradesh, India (latitude: 30° 52' 30" N, longitude: 77° 11' 30" E), during the years 2022, 2023 and 2024. The meteorological data, including temperature (minimum/maximum), relative humidity as well as rainfall for the growing season, are presented in Fig. 1a, b

Planting material

Okra is known to be predominantly a cross-pollinated vegetable species, exhibiting a somatic chromosome number of $2n = 130$ ¹⁵. It is believed to be an amphidiploid, resulting from the hybridization of *Abelmoschus tuberculatus* ($2n = 58$) and an unidentified species characterized by $2n = 72$ chromosomes¹⁶. The study utilized 14 distinct genotypes, comprising 10 parental lines and 4 testers. The selection of okra lines and testers prioritized traits that enhance adaptability and productivity under the prevailing climatic conditions of the sub-mountain Himalayan region. Specifically, the selected parents are early in flowering and maturity due to the limited growing season. Additionally, the outlined conditions were also unfavorable for the whitefly (*Bemisia tabaci*), which serves as the primary vector for YVMV, enabling plants to reach their maximum potential and strengthening the breeding program. The parental lines were provided by the Department of Vegetable Science at Dr. Yashwant Singh Parmar University of Horticulture and Forestry (Solan), ICAR-Indian Institute of Vegetable Research Varanasi, and Chaudhary Charan Singh Haryana Agricultural University (Hisar, Haryana), while the testers were obtained from Chaudhary Charan Singh Haryana Agricultural University (Hisar, Haryana), CSK Himachal Pradesh Krishi Vishvavidyalaya Palampur, Punjab Agricultural University Ludhiana, and ICAR-Indian Institute of Vegetable Research Varanasi. During the rainy season of 2022 (first week of May), parental plants were sown at a spacing of 60 cm × 20 cm to produce 40 crosses. Information about the parental lines, testers, and



(a)



(b)

Fig. 1. (a) Weather data trends (rainfall, temperature, relative humidity) throughout the 2023 investigation period. (b) Weather data trends (rainfall, temperature, relative humidity) throughout the 2024 investigation period.

their F_1 hybrids is provided in Supplementary Table 2. Seed produced from the fourteen parental lines and 40 F_1 hybrids during the first season was planted in a Randomized Complete Block Design (RCBD) with three replications, spaced at 60 cm × 20 cm. A commercial variety named Punjab-8 (developed by PAU, Ludhiana, Punjab) was used as the standard check in the rainy seasons of 2023 (first week of June) and 2024 (first week of June) to evaluate standard heterosis over 2 years. The pooled data collected over these 2 years were analyzed for 14 horticultural traits. Recommended cultural practices for healthy okra crop production, as outlined in the “Package of Practices for Vegetable Crops” by Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh, were followed. Observations were recorded over 2 years, 2023 and 2024, for various 14 quantitative traits: DFF (Days to 50% flowering), FFN (First fruiting node), IL (Internodal length in cm), PH (Plant height in cm), LL (Leaf length in cm), LW (Leaf width in cm), FL (Fruit length in cm), FD (Fruit diameter in mm), NRPF (Number of ridges per fruit), FW (Fruit weight in g), NFPP (Number of fruits per plant), NSPF (Number of seeds per fruit), HSW (Hundred seed weight in g), and FYPP (Fruit yield per plant in g). Data collection was carried out on ten randomly selected and tagged plants for each genotype in each replication.

Statistical analysis

The Analysis of Variance (ANOVA) and F-Test were utilized to evaluate the RCBD (Randomized Complete Block Design) following the approach as described by Panse and Sukhatme¹⁷. Mean values for the each trait were

calculated by dividing the total values (observed) by the total number of observations. Heterosis was assessed by measuring the percentage increase or decrease in mean F_1 performance relative to better parent and the standard check, using the approach detailed by Fonseca and Patterson¹⁸. The statistical significance was determined using the T-test and standard error as described by Wynne et al.¹⁹. The combining ability analysis for the Line \times Tester mating design followed Kempthorne's¹³ guidelines and was performed using Microsoft Excel 365 along with the OP-STAT software developed by the scientist Sheoran et al.²⁰.

Analysis of variance

The pooled analysis of variance conducted on 54 genotypes for diverse quantitative traits revealed highly significant differences among parents, crosses, and the standard check. Pooled variance from the combined line \times tester ANOVA has been distributed into the variances due to the lines, testers, lines vs. testers, crosses as well as parents vs. crosses. Notably, parents and crosses exhibited significant variations across all studied traits and their ANOVA has been presented in supplementary file (Table 1). The overall pooled mean performance of the parental lines, crosses, and standard check is illustrated in Fig. 2.

Results

Heterotic studies

Better parent heterosis

The F_1 hybrid exhibits a pronounced superiority in comparison to its better parent. This phenomenon is often referred to as "Heterobeltiosis". The data related to heterobeltiosis has been presented in Tables 1 and 2. For earliness traits, heterosis in negative direction is desirable for early harvests that increases the overall yield of the crop. Among forty cross combinations, seven cross combinations showed significantly negative heterotic response over better parent for days to 50 per cent flowering. Eight crosses revealed significant and negative heterotic response over better parent for the first fruiting node as well as for internodal length. This may be beneficial for initiatives focused on developing early-maturing okra cultivars.

Three crosses recorded with considerable significant heterotic response in positive direction over better parent for trait plant height. Thirteen crosses showed significant and positive heterotic response over better parent for leaf length. For leaf width, three cross combinations showed significant heterotic response over better parent in positive direction. Nine cross combinations demonstrated significant and positive heterotic response over better parent for fruit length. The heterotic response of two crosses were observed significant in positive direction over better parent for fruit diameter. Nine cross combinations each exhibited significantly positive heterotic response for number of ridges on fruit. Seven crosses exhibited significant and positive heterosis response over better parent for fruit weight. For number of fruits per plant, eighteen cross combinations revealed significant heterotic response in positive direction.

where, DFF: Days to 50 per cent flowering, FFN: First fruiting node; IL: Internodal length (cm), PH: Plant height (cm), LL: Leaf length (cm), LW: Leaf width (cm), FL: Fruit length (cm).

where, FD: Fruit diameter (mm), NRPF: Number of ridges per fruit, FW: Fruit weight (g), NFPP: Number of fruit, NSPF: Number of seeds per fruit, HSW: Hundred seed weight (g), FYPP: Fruit yield per plant (g).

Eight crosses showed considerable heterotic response for number of seeds per fruit in the positive direction. Nine cross combinations were recorded with significant and positive heterotic response over better parent for hundred seed weight. Positive and significant heterotic response for fruit yield per plant was exhibited for fourteen cross combinations over better parent and these hybrids resulted in increase in the overall yield. The hybrids with considerable amount of heterosis for seed traits resulted in increased reproductive success rate and viability of seed.

Economic heterosis

The superiority of the F_1 hybrid in relation to the high-yielding local variety or cultivar within a specific geographical area is known as economic heterosis. Economic heterosis represents a significant extent in plant breeding, signifying the potential for improved performance in comparison to the present popular cultivars. The data on economic heterosis has been presented in Tables 3 and 4.

where, DFF: Days to 50 per cent flowering, FFN: First fruiting node, IL: Internodal length (cm), PH: Plant height (cm), LL: Leaf length (cm), LW: Leaf width (cm), FL: Fruit length (cm).

where, FD: Fruit diameter (mm), NRPF: Number of ridges per fruit, FW: Fruit weight (g), NFPP: Number of fruit, NSPF: Number of seeds per fruit, HSW: Hundred seed weight (g), FYPP: Fruit yield per plant (g).

Thirteen cross combinations exhibited significantly negative heterotic response over standard check for days to 50 per cent flowering. For first fruiting node, eleven crosses showed significant and negative heterotic response over standard check. For five crosses, significant heterotic response was recorded for internodal length in negative direction. Fifteen crosses were observed with significantly positive heterotic response over local variety for plant height. Twenty one crosses for leaf length and sixteen crosses for leaf width showed significant and positive response of heterosis over local variety. Eighteen cross combinations exhibited significant heterotic response for fruit length in positive direction. None of the forty cross combinations showed significant and positive heterotic response for fruit diameter. Thirteen crosses demonstrated significant and positive heterotic response over local cultivar for number of ridges per fruit. For fruit weight, twenty seven crosses revealed significant heterotic response in positive direction while seventeen cross combinations exhibited significantly positive heterosis over commercial cultivar for number of fruits per plant. Six crosses for number of seeds per fruit and eleven crosses for hundred seed weight demonstrated significant heterotic response in positive direction. Among forty cross combinations, three crosses exhibited significant heterotic response for fruit yield per plant in positive direction.

Hybrids	Traits						
	DFF	FFN	IL	PH	LL	LW	FL
COHF N-1 × Varsha Uphar	-1.49	-12.71	-28.32*	2.06	22.71*	16.55*	5.39
COHF N-1 × Palam Komal	7.29*	19.51	-19.57	7.51*	6.95*	2.99	16.10*
COHF N-1 × Punjab Suhabani	-16.39*	-0.33	-31.82*	7.18	3.07	1.25	-21.65*
COHF N-1 × Kashi Chaman	-2.60	31.01*	-11.91	10.02*	7.68*	11.62*	1.69
COHF N-2 × Varsha Uphar	15.16*	-13.74	-13.89	-2.45	7.59*	-6.60*	11.14*
COHF N-2 × Palam Komal	3.73	21.64	-22.17*	6.11	6.07	-13.32*	-8.26*
COHF N-2 × Punjab Suhabani	-4.68	28.31*	-4.80	2.7	6.23*	-4.89	-1.10
COHF N-2 × Kashi Chaman	2.56	14.44	6.15	6.67	-2.48	-11.09*	3.13
COHF N-9 × Varsha Uphar	0.12	19.64*	-19.97*	0.15	3.46	-7.89*	19.77*
COHF N-9 × Palam Komal	4.18	4.35	8.76	1.58	-1.30	-14.47*	7.15
COHF N-9 × Punjab Suhabani	-0.88	11.16	14.58	4.68	5.89	-9.62*	-0.56
COHF N-9 × Kashi Chaman	-8.37*	-8.18	5.23	3.34	-0.03	-4.09	-16.13*
COHF N-11 × Varsha Uphar	13.52*	-21.88*	-18.83*	-2.85	25.47*	4.23	3.77
COHF N-11 × Palam Komal	6.16	90.60*	-1.92	8.53*	24.85*	4.35	-2.23
COHF N-11 × Punjab Suhabani	-2.90	-37.89*	-1.19	4.04	11.78*	3.31	-6.40
COHF N-11 × Kashi Chaman	6.88*	-30.10*	-17.56	6.02	1.57	0.56	-10.21*
UHF-Okra-2 × Varsha Uphar	9.88*	-41.73*	-20.64*	-33.04*	4.16	2.14	-7.62*
UHF-Okra-2 × Palam Komal	-10.18*	58.54*	-11.72	-19.62*	0.22	0.16	-21.94*
UHF-Okra-2 × Punjab Suhabani	-12.56*	-20.57	1.51	-11.24*	5.98	1.73	-5.18
UHF-Okra-2 × Kashi Chaman	-7.56*	11.31	-13.44	-21.19*	-3.85	-0.24	-9.21*
UHF-Okra-4 × Varsha Uphar	14.91*	-39.48*	0.88	-3.58	6.28	-1.20	-4.63
UHF-Okra-4 × Palam Komal	-0.34	-16.68	6.63	1.95	4.83	-10.30*	-11.90*
UHF-Okra-4 × Punjab Suhabani	3.51	-13.82	1.12	0.33	2.23	-3.92	7.27*
UHF-Okra-4 × Kashi Chaman	1.70	12.42	-17.71	5.02	-5.79*	-5.30	-4.76
Kashi Vibhuti × Varsha Uphar	11.58*	-14.59	-0.36	-7.91*	3.09	-1.42	12.50*
Kashi Vibhuti × Palam Komal	0.05	-6.98	11.31	-3.18	3.11	0.46	7.01
Kashi Vibhuti × Punjab Suhabani	-1.22	-14.49	1.33	-2.35	2.73	2.53	-6.16
Kashi Vibhuti × Kashi Chaman	-0.54	-30.10*	-43.77*	-3.16	-5.68*	-4.65	-13.36*
Kashi Mahima × Varsha Uphar	-2.30	7.00	-12.06	-5.26	18.08*	-6.31*	10.72*
Kashi Mahima × Palam Komal	5.16	-15.62	5.43	-1.38	7.88*	-6.67*	-4.58
Kashi Mahima × Punjab Suhabani	-2.58	-4.56	-0.5	-2.68	10.79*	-2.22	9.59*
Kashi Mahima × Kashi Chaman	-4.77	-30.02*	-20.22*	-15.86*	-0.54	-0.26	-17.82*
Kashi Pragati × Varsha Uphar	-3.70	25.00	7.81	-2.63	16.38*	-2.92	3.76
Kashi Pragati × Palam Komal	-4.11	-18.12	-18.21	0.63	0.60	-13.97*	-4.41
Kashi Pragati × Punjab Suhabani	-6.51	-17.09	7.52	-6.29*	10.50*	-3.98	6.81*
Kashi Pragati × Kashi Chaman	-8.00*	-7.11	5.75	-11.55*	-0.54	-3.2	-10.68*
Kashi Satdhari × Varsha Uphar	1.53	20.37	11.34	2.75	-4.81	-1.43	17.25*
Kashi Satdhari × Palam Komal	4.96	-15.53	39.18*	-1.78	0.94	12.06*	0.06
Kashi Satdhari × Punjab Suhabani	-9.15*	-6.07	10.37	-3.32	-4.32	-2.19	-0.03
Kashi Satdhari × Kashi Chaman	2.15	-28.81*	-13.34	-13.76*	-17.72*	-12.77*	-0.61

Table 1. Pooled assessment of better parent heterosis (%) in okra for various traits using a line × tester mating fashion. *significant at 5 percent level, respectively.

Combining ability effects

General combining ability (GCA)

The GCA is referred as the average performance of a genotype in a group of hybrid combinations. Parents who consistently exhibit good combinations are perceived to possess superior General Combining Ability (GCA). The variations in GCA can primarily be due to additive genetic effects and interactions of a higher-order additive genes. The genotypes exhibiting significantly positive GCA effects shows its positive impact on the expression of particular traits. The higher negative GCA effects for earliness traits are desirable as it leads to early harvest and higher yields. Table 5 represented the data on GCA. UHF-Okra-2 Kashi Pragati, Kashi Mahima, Kashi Satdhari and Punjab Suhabani showed significantly negative GCA effects for days to 50 per cent flowering. For first fruiting node, Kashi Vibhuti, Kashi Pragati, Kashi Mahima, Kashi Satdhari and Kashi Chaman had negative and significant GCA effects. COHF N-1, COHF-N-2 and Kashi Chaman exhibited significantly negative GCA effects for internodal length. For plant height, Kashi Pragati, UHF-Okra-4, Palam Komal and Punjab Suhabani had significantly positive GCA effects. COHF N-11, COHF N-1, Kashi Mahima, Kashi Chaman and Punjab Suhabani

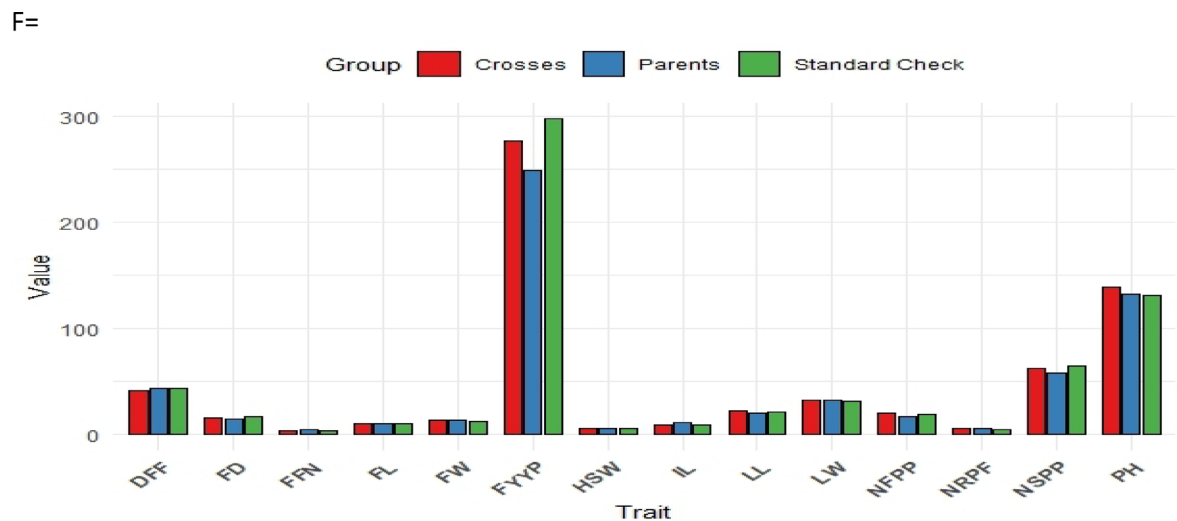


Fig. 2. The overall pooled mean performance of the parental lines, crosses and standard check for 14 different traits Where, DFF: Days to 50 per cent flowering, FFN: First fruiting node; IL: Internodal length (cm), PH: Plant height (cm), LL: Leaf length (cm), LW: Leaf width (cm), FL: Fruit length (cm), FD: Fruit diameter (mm), NRPF: Number of ridges per fruit, FW: Fruit weight (g), NFPP: Number of fruit, NSPP: Number of seeds per fruit, HSW: Hundred seed weight (g), FYPP: Fruit yield per plant (g).

for leaf length whereas COHF N-1, COHF N-11 and Kashi Chaman for leaf width revealed significant GCA effects in positive direction. For fruit length, Kashi Satdhari, Varsha Uphar, UHF-Okra-4 and Punjab Suhabani had significantly positive GCA effects whereas for fruit diameter, Kashi Satdhari, COHF N-9, Varsha Uphar and Palam Komal showed significantly positive GCA effects. Kashi Satdhari, COHF N-9 and Palam Komal revealed significant and positive GCA effects for number of ridges on fruit. For fruit weight, Kashi Satdhari, Kashi Mahima and COHF N-9 had significantly positive GCA effects whereas for number of fruits per plant, Kashi Pragati, COHF N-2, UHF-Okra-2, Punjab Suhabani, Kashi Satdhari and COHF N-11 revealed significant and positive GCA effects. Kashi Satdhari, COHF N-9, Palam Komal and COHF N-1 showed significant and positive GCA effects for number of seeds per fruit whereas for 100 seed weight, COHF N-2, UHF-Okra-2 and Palam Komal had significantly positive GCA effects. For fruit yield per plant, Kashi Pragati, Kashi Satdhari, Punjab Suhabani and COHF N-9 showed significantly positive GCA effects. Identifying genotypes with significant and desirable general combining ability (GCA) effects for important traits can aid in selecting parental lines for breeding superior hybrids of okra. Breeders can also give priority to genotypes like Kashi Pragati, Kashi Satdhari, Punjab Suhabani and COHF N-9 for improvement in targeted traits contributing to hybrids with superior growth, yield, and quality attributes.

where, DFF: Days to 50 per cent flowering, FFN: First fruiting node, IL: Internodal length (cm), PH: Plant height (cm), LL: Leaf length (cm), LW: Leaf width (cm), FL: Fruit length (cm), FD: Fruit diameter (mm), NRPF: Number of ridges per fruit, FW: Fruit weight (g), NFPP: Number of fruit, NSPP: Number of seeds per fruit, HSW: Hundred seed weight (g), FYPP: Fruit yield per plant (g).

Specific combining ability (SCA)

SCA refers to the average performance of parental lines in specific cross combinations. These effects occur when diverse genotype crosses are assessed for traits associated with plant development, yield, and biochemical properties. SCA evaluates the relative performance of specific crosses, with significant positive or negative SCA effects reflecting the influence of the particular combination on the desirable traits. Tables 6 and 7 and Supplementary Fig. 2 presents the data on the SCA. Among forty crosses, COHF N-1 × Punjab Suhabani, UHF-Okra-2 × Palam Komal, UHF-Okra-4 × Palam Komal, COHF N-9 × Varsha Uphar and COHF N-1 × Varsha Uphar had significantly negative SCA effects for days to 50 per cent flowering. For first fruiting node, UHF-Okra-2 × Varsha Uphar, COHF N-11 × Punjab Suhabani, COHF N-11 × Kashi Chaman, COHF N-9 × Palam Komal and COHF N-9 × Kashi Chaman revealed significant SCA effects in negative direction. Kashi Vibhuti × Kashi Chaman, Kashi Pragati × Palam Komal, Kashi Satdhari × Kashi Chaman, COHF N-9 × Varsha Uphar and COHF N-2 × Palam Komal had negative and significant SCA effects for trait internodal length. For trait plant height, UHF-Okra-4 × Kashi Chaman, Kashi Satdhari × Varsha Uphar, UHF-Okra-2 × Punjab Suhabani and UHF-Okra-2 × Kashi Chaman displayed significant and positive SCA effects. Crosses COHF N-11 × Palam Komal, Kashi Satdhari × Palam Komal, COHF N-1 × Varsha Uphar, COHF N-1 × Kashi Chaman and COHF N-9 × Kashi Chaman for leaf length whereas Kashi Satdhari × Palam Komal, COHF N-1 × Kashi Chaman, COHF N-1 × Varsha Uphar, COHF N-11 × Palam Komal and Kashi Vibhuti × Punjab Suhabani exhibited significantly positive SCA effects. For fruit length, crosses COHF N-1 × Palam Komal, COHF N-1 × Kashi Chaman, COHF N-2 × Kashi Chaman, Kashi Mahima × Punjab Suhabani, Kashi Pragati × Punjab Suhabani, UHF-Okra-4 × Punjab Suhabani and COHF N-9 × Varsha Uphar displayed significant and positive

Hybrids	Traits						
	FD	NRPF	FW	NFPF	NSPF	HSW	FYPP
COHF N-1 × Varsha Uphar	3.36	3.78	-0.66	-10.15*	31.34*	8.44*	-6.25
COHF N-1 × Palam Komal	7.62	6.88*	6.19	12.09*	4.61	-3.61	16.53*
COHF N-1 × Punjab Suhabani	-15.59*	-6.01*	2.72	4.92	-3.38	2.89	6.40
COHF N-1 × Kashi Chaman	-5.01	7.97*	5.45	-4.16	4.31	-11.93*	-16.00*
COHF N-2 × Varsha Uphar	-1.05	0.26	-8.73*	14.64*	1.06	-1.72	7.91
COHF N-2 × Palam Komal	4.39	4.45	-12.76*	9.48*	12.42*	3.01	-4.19
COHF N-2 × Punjab Suhabani	-6.86	-7.09*	-4.83	17.11*	-11.00*	12.49*	12.14*
COHF N-2 × Kashi Chaman	0.87	1.23	4.53	8.83*	-0.90	3.46	-1.55
COHF N-9 × Varsha Uphar	4.62	19.86*	8.22*	6.67	9.78	17.09*	9.17*
COHF N-9 × Palam Komal	18.94*	12.55*	5.82	12.08*	16.73*	-17.50*	19.69*
COHF N-9 × Punjab Suhabani	-0.42	28.95*	16.30*	17.90*	13.71*	-0.56	31.78*
COHF N-9 × Kashi Chaman	-5.88	15.80*	-3.48	2.54	-2.12	-26.14*	-7.69*
COHF N-11 × Varsha Uphar	-3.15	-2.05	-1.93	20.02*	-3.66	11.36*	10.32*
COHF N-11 × Palam Komal	-6.70	2.74	-7.98*	13.57*	-6.26	-4.38	0.64
COHF N-11 × Punjab Suhabani	-11.43*	-9.49*	0.46	7.00	-25.34*	-1.26	-0.73
COHF N-11 × Kashi Chaman	-2.83	1.30	-4.56	-5.26	-17.90*	-11.11*	-11.68*
UHF-Okra-2 × Varsha Uphar	-1.89	1.60	-10.26*	2.68	1.50	-14.39*	-1.92
UHF-Okra-2 × Palam Komal	3.20	1.50	-14.56*	23.56*	-8.60	0.78	4.96
UHF-Okra-2 × Punjab Suhabani	-1.66	-5.89*	-3.25	38.05*	-17.75*	-8.95*	19.83*
UHF-Okra-2 × Kashi Chaman	-1.74	20.62*	-20.92*	19.46*	4.33	-4.87	-16.37*
UHF-Okra-4 × Varsha Uphar	-8.79*	0.96	1.92	-0.87	3.03	-14.48*	0.90
UHF-Okra-4 × Palam Komal	-10.43*	1.29	5.79	1.68	6.05	2.36	-0.37
UHF-Okra-4 × Punjab Suhabani	-10.43*	-6.97*	10.42*	8.23	-1.97	-0.52	20.04*
UHF-Okra-4 × Kashi Chaman	-10.02*	0.13	-6.83	-5.82	-3.81	-19.81*	-25.74*
Kashi Vibhuti × Varsha Uphar	-10.46*	1.47	0.62	12.17*	-4.19	8.49*	7.36
Kashi Vibhuti × Palam Komal	-3.62	19.63*	8.11	1.87	-11.84*	16.21*	16.80*
Kashi Vibhuti × Punjab Suhabani	-9.86*	-6.55*	-0.42	3.72	6.06	-0.84	4.52
Kashi Vibhuti × Kashi Chaman	-12.88*	-0.45	-4.72	5.64	-1.08	-16.67*	-7.20
Kashi Mahima × Varsha Uphar	-3.36	10.79*	8.99*	-2.31	-5.80	-24.25*	5.42
Kashi Mahima × Palam Komal	-3.63	0.19	-5.20	15.13*	2.80	-10.29*	12.42*
Kashi Mahima × Punjab Suhabani	2.91	-7.81*	15.76*	17.98*	-13.25*	-26.89*	36.24*
Kashi Mahima × Kashi Chaman	-3.42	-1.78	-9.86*	0.63	12.76*	-7.06*	-17.46*
Kashi Pragati × Varsha Uphar	-2.01	-0.70	-6.57	6.75	7.50	4.51	-8.74*
Kashi Pragati × Palam Komal	-2.01	-0.39	4.98	26.11*	-5.02	18.06*	19.98*
Kashi Pragati × Punjab Suhabani	-10.26*	-7.81*	1.90	27.79*	-30.77*	-18.32*	12.65*
Kashi Pragati × Kashi Chaman	-10.87*	2.19	-4.30	-1.23	-26.86*	-23.77*	-12.75*
Kashi Satdhari × Varsha Uphar	0.00	-14.30*	12.16*	3.99	42.97*	19.39*	-7.55
Kashi Satdhari × Palam Komal	14.44*	0.42	3.04	6.87	33.59*	16.48*	-13.41*
Kashi Satdhari × Punjab Suhabani	-8.52*	-13.70*	-1.34	61.13*	-6.18	-0.52	25.78*
Kashi Satdhari × Kashi Chaman	6.47	0.09	10.80*	-3.85	59.48*	-27.50*	-9.04*

Table 2. Pooled assessment of better parent heterosis (%) in okra for various traits using a line × tester mating fashion. *significant at 5 percent level, respectively.

SCA effects. Kashi Mahima × Punjab Suhabani, Kashi Satdhari × Palam Komal, COHF N-1 × Varsha Uphar and COHF N-9 × Palam Komal had significantly positive SCA effects for fruit diameter. For number of ridges on fruit, COHF N-9 × Punjab Suhabani, Kashi Vibhuti × Palam Komal, UHF-Okra-2 × Kashi Chaman, Kashi Mahima × Varsha Uphar, Kashi Satdhari × Palam Komal and Kashi Satdhari × Kashi Chaman displayed significant effects for SCA in positive direction. For trait fruit weight, COHF N-2 × Kashi Chaman, Kashi Mahima × Punjab Suhabani, COHF N-1 × Kashi Chaman, Kashi Pragati × Palam Komal, UHF-Okra-2 × Punjab Suhabani, Kashi Satdhari × Kashi Chaman and Kashi Vibhuti × Palam Komal whereas for number of fruits per plant, Kashi Satdhari × Punjab Suhabani, COHF N-11 × Varsha Uphar, Kashi Pragati × Palam Komal, UHF-Okra-4 × Varsha Uphar, UHF-Okra-2 × Punjab Suhabani, Kashi Vibhuti × Varsha Uphar, Kashi Pragati × Punjab Suhabani, Kashi Vibhuti × Kashi Chaman and COHF N-1 × Kashi Chaman had significantly positive SCA effects. For number of seeds per fruit, cross Kashi Vibhuti × Punjab Suhabani and for 100 seed weight cross COHF N-9 × Varsha Uphar showed higher significant SCA effects in positive direction. Crosses Kashi Satdhari × Punjab Suhabani, Kashi Pragati × Palam Komal, COHF N-2 × Kashi Chaman, UHF-Okra-4 × Varsha Uphar, COHF N-1 × Palam Komal,

Hybrids \	Traits						
	DFF	FFN	IL	PH	LL	LW	FL
COHF N-1 × Varsha Uphar	-10.77*	4.06	-29.40*	3.68	19.21*	18.22*	4.39
COHF N-1 × Palam Komal	6.83*	6.58	-20.78	9.78*	3.10	4.47	11.69*
COHF N-1 × Punjab Suhabani	-15.06*	7.94	-33.87*	9.43*	6.21*	5.31	-13.36*
COHF N-1 × Kashi Chaman	0.37	16.95	-13.23	-5.86	21.67*	21.13*	20.33*
COHF N-2 × Varsha Uphar	4.31	10.91	-22.28*	-0.90	4.53	-0.22	13.69*
COHF N-2 × Palam Komal	3.29	8.48	-29.75*	8.35*	-0.28	-7.40*	-6.16
COHF N-2 × Punjab Suhabani	-3.16	38.95*	-14.07	4.85	9.47*	1.61	9.36*
COHF N-2 × Kashi Chaman	4.21	2.16	-4.19	-8.73*	10.19*	-3.52	22.04*
COHF N-9 × Varsha Uphar	-9.31*	53.83*	-8.07	1.74	0.52	1.70	18.63*
COHF N-9 × Palam Komal	3.73	-6.94	10.51	3.72	-7.22*	-5.57*	3.08
COHF N-9 × Punjab Suhabani	0.70	20.38	11.14	6.87	9.12*	-0.21	9.95*
COHF N-9 × Kashi Chaman	-5.57	-18.03	13.16	-11.58*	12.96*	5.90**	-0.75
COHF N-11 × Varsha Uphar	2.83	0.45	-11.94	-1.31	21.90*	10.35*	2.78
COHF N-11 × Palam Komal	5.71	69.97*	-0.35	10.82*	18.35*	10.47*	-3.60
COHF N-11 × Punjab Suhabani	-1.35	-32.73*	-4.16	6.22	15.19*	9.37*	3.50
COHF N-11 × Kashi Chaman	9.11*	-37.60*	-11.35	-7.29	14.76*	9.12*	6.25
UHF-Okra-2 × Varsha Uphar	-0.46	-25.07*	-8.83	-16.47*	2.74	0.38	9.20*
UHF-Okra-2 × Palam Komal	-12.56*	41.39*	-10.30	0.27	-1.15	-2.36	-7.73
UHF-Okra-2 × Punjab Suhabani	-14.88*	-13.98	-1.54	10.72*	9.21*	5.80*	12.08*
UHF-Okra-2 × Kashi Chaman	-10.01*	-0.63	-6.91	-1.69	8.63*	8.25*	7.43
UHF-Okra-4 × Varsha Uphar	4.09	-22.18	7.79	17.87	3.25	6.75*	7.83
UHF-Okra-4 × Palam Komal	-1.21	-25.70*	8.34	24.63*	-1.45	-3.08	-0.39
UHF-Okra-4 × Punjab Suhabani	2.61	-6.67	-1.92	22.64*	5.35	3.82	21.28*
UHF-Okra-4 × Kashi Chaman	0.81	0.36	-12.08	28.38*	6.45*	2.77	12.70*
Kashi Vibhuti × Varsha Uphar	1.07	-23.44	14.46	-6.45	0.16	-3.12	11.43*
Kashi Vibhuti × Palam Komal	-0.37	-17.04	13.09	-1.14	-1.90	-1.34	2.95
Kashi Vibhuti × Punjab Suhabani	0.36	-23.35	-1.71	-0.31	5.86	6.64*	3.77
Kashi Vibhuti × Kashi Chaman	2.50	-37.60*	-39.53*	-10.13*	6.57*	3.48	2.52
Kashi Mahima × Varsha Uphar	-11.50*	-4.87	-6.60	7.04	14.72*	1.91	15.62*
Kashi Mahima × Palam Komal	-0.69	-24.98	7.12	11.42*	2.48	1.52	-0.36
Kashi Mahima × Punjab Suhabani	-7.99*	-15.15	-3.49	9.96*	14.17*	6.37*	21.19*
Kashi Mahima × Kashi Chaman	-10.07*	-37.78*	-15.26	-4.93	12.37*	8.50*	-2.75
Kashi Pragati × Varsha Uphar	-12.77*	-1.71	23.85*	26.89*	13.07*	6.80*	4.03
Kashi Pragati × Palam Komal	-4.51	-35.62*	-16.90	31.14*	-5.42	-5.36*	-4.16
Kashi Pragati × Punjab Suhabani	-6.41	-34.81*	4.29	22.13*	13.87*	5.63*	18.11*
Kashi Pragati × Kashi Chaman	-7.90*	-26.96*	13.72	15.27*	12.37*	6.49*	5.70
Kashi Satdhari × Varsha Uphar	-8.03*	5.50	27.90*	12.61*	-7.52*	-3.13	20.63*
Kashi Satdhari × Palam Komal	-0.36	-25.97*	41.41*	7.64	-5.11	3.40	2.95
Kashi Satdhari × Punjab Suhabani	13.75*	-17.67	7.05	5.96	-1.40	1.72	10.54*
Kashi Satdhari × Kashi Chaman	-3.03	-37.60*	-6.81	-5.48	-7.03*	-5.34	17.62*

Table 3. Pooled assessment of economic heterosis (%) in okra for various traits using a line × tester mating design. *significant at 5 percent level, respectively.

COHF N-1 × Kashi Chaman and UHF-Okra-2 × Punjab Suhabani displayed significantly positive SCA effects for fruit yield per plant.

Identifying crosses having significant SCA effects for desirable traits enables breeders in choosing parent combinations that enhance the performance of hybrid, resulting in the production of okra cultivars with superior performance. Positive effects for SCA for the yield and its contributing characters indicate that the hybrids can achieve high productivity as well as quality standards, thus helping both to the farmers as well as to the consumers. Cross combinations with negative significant effects for SCA for earliness traits can increase okra's market profitability as well as availability.

where, DFF: Days to 50 per cent flowering, FFN: First fruiting node, IL: Internodal length (cm), PH: Plant height (cm), LL: Leaf length (cm), LW: Leaf width (cm), FL: Fruit length (cm).

where, FD: Fruit diameter (mm), NRPF: Number of ridges per fruit, FW: Fruit weight (g), NFPP: Number of fruit, NSPF: Number of seeds per fruit, HSW: Hundred seed weight (g), FYPP: Fruit yield per plant (g).

Hybrids \	Traits						
	FD	NRPF	FW	NFPP	NSPF	HSW	FYPP
COHF N-1 × Varsha Uphar	-3.34	4.11	9.08*	-11.81*	14.47*	5.34	-17.84*
COHF N-1 × Palam Komal	-8.45*	6.88*	10.32*	-3.10	1.57	-3.19	-11.59*
COHF N-1 × Punjab Suhabani	-20.24*	0.58	5.13	-15.33*	-0.73	7.81	-27.68*
COHF N-1 × Kashi Chaman	-14.34*	7.97*	21.85*	-10.48*	-9.93	6.38	-14.42*
COHF N-2 × Varsha Uphar	-7.47*	0.58	0.22	19.38*	-11.92	-2.64	-5.43
COHF N-2 × Palam Komal	-11.20*	4.05	-7.81	14.01*	9.15	3.47	-16.22*
COHF N-2 × Punjab Suhabani	-11.98*	-0.58	0.57	21.95*	-8.56	17.88*	-1.94
COHF N-2 × Kashi Chaman	-9.04*	0.84	20.80*	13.33*	-14.43*	24.97*	0.30
COHF N-9 × Varsha Uphar	-2.16	23.33*	18.83*	4.71	7.86	26.24*	-4.33
COHF N-9 × Palam Komal	1.18	15.81*	9.94*	9.59*	14.68*	-11.06*	-7.17
COHF N-9 × Punjab Suhabani	-5.89	37.98*	15.07*	15.28*	16.83*	7.21	2.21
COHF N-9 × Kashi Chaman	-15.13*	19.15*	11.53*	0.27	-3.84	-10.78*	-5.96
COHF N-11 × Varsha Uphar	-9.43*	-1.74	9.89*	22.04*	-9.10	4.57	3.04
COHF N-11 × Palam Komal	-20.63*	1.35	3.11	15.48*	-8.98	-3.96	-6.00
COHF N-11 × Punjab Suhabani	-16.31*	-3.15	12.56*	8.80*	-23.30*	3.47	-7.28
COHF N-11 × Kashi Chaman	-12.38*	0.06	10.29*	-3.67	-22.53*	7.37	-10.02*
UHF-Okra-2 × Varsha Uphar	-8.25*	1.93	3.05	0.79	-10.29	-3.14	-14.05*
UHF-Okra-2 × Palam Komal	-11.39*	-0.26	-1.89	14.76*	-11.26	14.03*	-10.90*
UHF-Okra-2 × Punjab Suhabani	-7.07*	0.71	11.10*	28.22*	-15.50*	3.03	1.72
UHF-Okra-2 × Kashi Chaman	-11.39*	19.15*	-8.62*	11.58*	-7.79	14.91*	-14.80*
UHF-Okra-4 × Varsha Uphar	-12.38*	1.29	11.91*	-2.70	-2.71	-10.34*	-11.58*
UHF-Okra-4 × Palam Komal	-13.95*	1.09	13.56*	-12.10*	2.97	7.32	-24.41*
UHF-Okra-4 × Punjab Suhabani	-13.95*	-0.45	18.53*	-12.67*	0.71	4.29	-18.41*
UHF-Okra-4 × Kashi Chaman	-13.56*	-0.06	7.67	-12.04*	-9.17	-3.14	-24.35*
Kashi Vibhuti × Varsha Uphar	-12.57*	1.80	10.48*	14.98*	-16.50*	1.87	-5.92
Kashi Vibhuti × Palam Komal	-5.89	19.86*	12.32*	4.42	-14.40*	16.72*	-1.40
Kashi Vibhuti × Punjab Suhabani	-11.98*	0.00	2.30	6.32	8.96	3.91	-11.76*
Kashi Vibhuti × Kashi Chaman	-14.93*	-0.26	10.10*	8.28	-14.59*	0.66	-5.46
Kashi Mahima × Varsha Uphar	-9.63*	12.21*	21.20*	-4.12	-6.55	-10.12*	-7.62
Kashi Mahima × Palam Komal	-11.39*	1.48	5.43	-0.47	1.98	6.44	-14.70*
Kashi Mahima × Punjab Suhabani	-2.75	-1.35	28.74*	-4.80	-10.88	-13.26*	-3.23
Kashi Mahima × Kashi Chaman	-11.20*	-0.51	4.16	-6.01	11.86	12.27*	-15.91*
Kashi Pragati × Varsha Uphar	-4.32	-0.39	6.32	14.85*	-6.32	9.52*	-5.58
Kashi Pragati × Palam Komal	-4.32	-0.84	19.48*	35.68*	-7.78	23.71*	24.14*
Kashi Pragati × Punjab Suhabani	-12.38*	-1.35	15.96*	37.48*	-28.87*	-14.41*	16.56*
Kashi Pragati × Kashi Chaman	-12.97*	1.74	10.59*	6.26	-36.84*	-7.92*	-9.72*
Kashi Satdhari × Varsha Uphar	-6.48*	18.64*	24.61*	2.08	24.60*	12.10*	-5.54
Kashi Satdhari × Palam Komal	4.32	39.01*	14.48*	0.41	29.71*	17.00*	-11.53*
Kashi Satdhari × Punjab Suhabani	-13.56*	19.47*	9.62*	51.39*	-3.61	4.24	28.52*
Kashi Satdhari × Kashi Chaman	-2.95	38.56*	28.04*	-9.66*	37.70*	-12.43*	-7.06

Table 4. Pooled assessment of economic heterosis (%) in okra for various traits using a line × tester mating fashion. *significant at 5 percent level, respectively.

Discussion

The present investigation revealed significant heterotic responses across multiple quantitative traits in okra, with several cross combinations exhibiting superior performance over both the better parent and standard check. Positive heterosis for traits such as fruit yield per plant, fruit length, fruit diameter, number of fruits per plant, and hundred seed weight suggests the presence of dominant and epistatic gene interactions, which are favorable for hybrid development. Notably, crosses like Kashi Mahima × Punjab Suhabani, COHF N-9 × Punjab Suhabani, and Kashi Satdhari × Punjab Suhabani consistently demonstrated high heterotic effects, making them promising combinations for commercial exploitation. Conversely, negative heterosis observed for traits like days to 50% flowering and first fruiting node in crosses such as COHF N-1 × Punjab Suhabani and UHF-Okra-2 × Punjab Suhabani is desirable for breeding early-maturing cultivars. These findings align with previous studies by Verma and Sood²¹, Karadi and Hanchinamani²², Yadav et al.²³, Pathania et al.⁹, and Patel et al.²⁴, who also reported significant heterotic responses in okra hybrids for yield-related traits. In terms of combining ability, the study highlighted the importance of both general and specific combining ability effects in determining

Parent(s)	Trait(s)													
	DFP	FFN	IL (cm)	PH (cm)	LL (cm)	LW (cm)	FL (cm)	FD (cm)	NRPF	FW (g)	NFPP	NSPF	HSW (g)	FYPP
Line(s)														
COHF N -1	-0.72	0.57*	-2.01*	-2.22	1.28*	2.79*	-0.16	-0.30	-0.12	0.10	-3.17*	3.02*	0.00	-32.18*
COHF N -2	2.22*	0.81*	-1.35*	-6.64*	-0.11	-1.83*	0.24	-0.02	-0.31*	-0.90*	1.93*	-2.01	0.42*	3.75
COHF N -9	0.16	0.70*	0.95*	-7.56*	-0.56*	-0.94*	0.04	0.73*	0.87*	0.38*	0.12	7.89*	-0.05	9.75*
COHF N -11	3.04*	0.25	-0.37	-5.04*	2.34*	2.02*	-0.52*	-0.84*	-0.42*	-0.22	0.71*	-8.17*	-0.07	6.01
UHF-Okra-2	-2.80*	0.26	-0.34	-10.16*	-0.35	-0.13	-0.21	0.04	-0.10	-1.22*	1.30*	-5.09*	0.19*	-7.22
UHF-Okra-4	1.96*	-0.25	0.36	22.92*	-0.66*	-0.27	0.31*	-0.62*	-0.35*	0.27	-3.11*	0.83	-0.27*	-37.55*
Kashi Vibhuti	1.67*	-0.69*	-0.01	-13.72*	-0.81*	-0.64*	-0.22	-0.26	-0.10	-0.26	0.31	-3.75*	0.11	2.83
Kashi Mahima	-1.98*	-0.52*	-0.12	-0.09	0.94*	0.36	0.11	0.18	-0.22*	0.51*	-1.99*	1.57	-0.31*	-9.78*
Kashi Pragati	-2.12*	-0.67*	0.91*	23.52*	0.42	-0.01	-0.15	0.22	-0.38*	0.29	3.12*	-10.74*	-0.08	40.03*
Kashi Satdhari	-1.43*	-0.45*	1.97*	-1.00	-2.49*	-1.35*	0.57*	0.87*	1.13*	1.04*	0.79*	16.43*	0.07	24.37*
S.E. (gi) (lines) ±	0.51	0.16	0.37	1.90	0.23	0.30	0.14	0.19	0.28	0.18	0.28	1.42	0.08	4.48
S.E. (gi-gj) (lines) ±	0.72	0.23	0.53	2.68	0.32	0.43	0.20	0.27	0.40	0.26	0.40	2.02	0.12	6.34
Tester(s)														
Varsha Uphar	-0.46	0.24*	0.19	-1.94	0.16	0.17	0.35*	0.37*	-0.05	0.10	-0.15	1.09	-0.04	-1.20
Palam Komal	1.28*	0.21*	0.34	6.20*	-1.35*	-1.25*	-0.77*	0.28*	0.08*	-0.35*	0.19	3.29*	0.18*	-2.67
Punjab Suhabani	-1.26*	-0.04	-0.05	5.12*	0.47*	0.37	0.23*	-0.31*	-0.11*	0.15	1.27*	-2.02*	-0.10	14.76*
Kashi Chaman	0.44	-0.42*	-0.47*	-9.39*	0.72*	0.71*	0.18	-0.34*	0.08	0.11	-1.32*	-2.34*	-0.05	-10.90*
S.E. (gi) (testers) ±	0.32	0.10	0.23	1.20	0.14	0.19	0.09	0.12	0.18	0.11	0.18	0.90	0.05	2.83
S.E. (gi-gj) (testers) ±	0.46	0.14	0.33	1.69	0.20	0.27	0.12	0.17	0.25	0.16	0.25	1.27	0.07	4.01
Good combiners	5	5	3	4	5	3	4	4	3	3	6	4	3	4
Poor combiners	5	5	3	6	5	5	2	4	6	3	4	6	2	4
Average combiners	4	4	8	4	4	6	8	6	5	8	4	4	9	6

Table 5. Pooled assessment of the GCA (general combining ability) for 14 traits in line × tester mating fashion of okra. *significant at 5 percent level, respectively.

hybrid performance. Parents such as EC755648, HB-20-3-4, HM-1, Neri-7, and Neri-9 exhibited strong general combining ability (GCA) for fruit yield and associated traits, indicating the predominance of additive gene action and their suitability for recurrent selection and population improvement by utilizing these superior parents in the hybridization programme. The results recorded for GCA effects aligned with the work conducted by Sidapara et al.²⁵, Kumar et al.⁸, Rasheed et al.²⁶ and Chakraborty et al.²⁷. Meanwhile, several hybrids demonstrated high specific combining ability (SCA), reflecting the influence of non-additive gene action and the potential for exploiting hybrid vigor. Crosses like Kashi Pragati × Palam Komal, COHF N-9 × Varsha Uphar, and Kashi Satdhari × Varsha Uphar showed notable SCA effects, reinforcing their value in heterosis breeding programs. These observations are consistent with the findings of Nanthakumar et al.²⁸, Narkhede et al.²⁹, Patel et al.³⁰ and Vekariya et al.³¹, who highlighted the role of SCA in enhancing fruit yield and other agronomic traits in okra. Furthermore in maize crop, Kumar et al.³² and Tabu et al.³³ and also highlighted the role of line-by-tester analysis and multi-environment evaluations in identifying superior hybrids for grain yield and provitamin A content. Singh³⁴ further emphasized the predictive power of genetic distance and combining ability for F₁ performance. Similar approaches have been applied in sorghum³⁵, field mustard²⁷, linseed²⁶ and hybrid rice³⁶, highlighting the universal significance of these genetic tools in crop improvement.

The heterosis observed in okra hybrids is primarily attributed to over dominance, as the heterozygous state confers genetic and physiological benefits, leading to enhanced plant performance in terms of yield and associated traits during both the years. The heterotic response is due to the integration of complementary alleles contributed by both parental lines. To use the genetic potential of the hybrids as well as the parental lines with good performance completely, okra breeding should focus on hybrid vigor, ability to combine traits, contributions of different genotypes and the potency ratios. The heterosis recorded in okra F₁ hybrids is driven by key genetic principles, including the genetic variation, epistatic interactions, and the benefits of heterozygosity. These fundamental biological principles might be strategically utilized in the agricultural systems to develop F₁ hybrids with superior performance. By integrating such principles, breeding programs can contribute significantly to sustainable agricultural practices, enhance crop resilience to climate variability and can also address challenges related to global food security. The findings of this study holds a considerable significance, providing critical insights for enhancing the breeding of okra and the advancements have the potential to provide substantial economic gains and contribute to improving agricultural productivity and sustainability. Several traits exhibiting significant heterotic response in desirable direction, including fruit yield per plant as well as several other yield associated traits that are governed by the multiple genes. Quantitative trait loci (QTL) mapping and genome-wide association studies (GWAS) are effective methods for identifying genomic regions associated with traits controlled by multiple genes³⁷. Conducting multi-location trials across various agro-climatic zones is essential to assess the stability as well as adaptability of the superior performing cultivars recognized during preliminary

Cross(s)	Trait(s)						
	DFE	FFN	IL (cm)	PH (cm)	LL (cm)	LW(cm)	FL (cm)
COHF N-1 × Varsha Uphar	-2.17*	-0.41	-0.67	1.18	1.25*	1.71*	-0.49
COHF N-1 × Palam Komal	3.67*	-0.29	0.00	1.05	-0.66	-1.22*	1.37*
COHF N-1 × Punjab Suhabani	-3.23*	0.00	-0.86	1.66	-1.81*	-2.57*	-2.18*
COHF N-1 × Kashi Chaman	1.73	0.71*	1.53*	-3.90	1.21*	2.08*	1.30*
COHF N-2 × Varsha Uphar	1.39	-0.39	-0.64	-0.42	-0.47	0.51	0.05
COHF N-2 × Palam Komal	-0.79	-0.46	-1.50*	3.60	0.02	-0.33	-0.85*
COHF N-2 × Punjab Suhabani	-1.04	0.92*	0.39	0.07	0.27	0.89	-0.27
COHF N-2 × Kashi Chaman	0.44	-0.07	1.75*	-3.25	0.17	-1.07	1.07*
COHF N-9 × Varsha Uphar	-2.42*	1.30*	-1.60*	3.97	-0.87	0.23	0.76*
COHF N-9 × Palam Komal	1.46	-0.92*	0.03	-1.56	-1.00*	-0.65	0.29
COHF N-9 × Punjab Suhabani	2.68*	0.34	0.48	3.65	0.65	-0.58	-0.01
COHF N-9 × Kashi Chaman	-1.72	-0.71*	1.09	-6.07	1.21*	1.01	-1.04*
COHF N-11 × Varsha Uphar	-0.07	-0.22	-0.67	-2.56	0.76	0.00	-0.30
COHF N-11 × Palam Komal	-0.58	2.38*	0.29	5.24	1.52*	1.45*	0.17
COHF N-11 × Punjab Suhabani	-1.08	-1.17*	0.32	0.27	-0.97*	-0.51	-0.10
COHF N-11 × Kashi Chaman	1.73	-0.98*	0.05	-2.95	-1.31*	-0.93	0.23
UHF-Okra-2 × Varsha Uphar	4.35*	-1.18*	-0.37	-17.34*	-0.61	-1.00	0.05
UHF-Okra-2 × Palam Komal	-2.61*	1.30*	-0.66	-3.49	0.07	-0.45	-0.55
UHF-Okra-2 × Punjab Suhabani	-1.07	-0.49	0.56	11.31*	0.46	0.51	0.46
UHF-Okra-2 × Kashi Chaman	-0.67	0.37	0.47	9.52*	0.08	0.94	0.04
UHF-Okra-4 × Varsha Uphar	1.55	-0.56	0.50	-5.30	-0.19	1.15	-0.61*
UHF-Okra-4 × Palam Komal	-2.48*	-0.66	0.41	-4.56	0.32	-0.53	-0.33
UHF-Okra-4 × Punjab Suhabani	1.70	0.29	-0.18	-6.10	-0.06	0.02	0.88*
UHF-Okra-4 × Kashi Chaman	-0.77	0.92*	-0.73	15.95*	-0.07	-0.64	0.06
Kashi Vibhuti × Varsha Uphar	0.54	-0.17	1.52*	-0.61	-0.69	-1.60*	0.28
Kashi Vibhuti × Palam Komal	-1.82	0.10	1.24	-1.78	0.38	0.38	0.54
Kashi Vibhuti × Punjab Suhabani	1.03	0.11	0.21	0.39	0.21	1.28*	-0.38
Kashi Vibhuti × Kashi Chaman	0.25	-0.05	-2.97*	2.00	0.11	-0.06	-0.45
Kashi Mahima × Varsha Uphar	-1.24	0.35	-0.38	3.47	0.64	-1.01	0.38
Kashi Mahima × Palam Komal	1.69	-0.37	0.78	1.09	-0.44	0.28	-0.13
Kashi Mahima × Punjab Suhabani	1.07	0.24	0.15	0.24	0.22	0.20	1.07*
Kashi Mahima × Kashi Chaman	-1.52	-0.22	-0.55	-4.80	-0.41	0.53	-1.32*
Kashi Pragati × Varsha Uphar	-1.64	0.62	1.49	5.92	0.81	0.91	-0.55
Kashi Pragati × Palam Komal	0.18	-0.61	-2.55*	3.37	-1.60*	-1.51*	-0.26
Kashi Pragati × Punjab Suhabani	1.90	-0.33	-0.13	-7.40	0.68	0.34	1.01*
Kashi Pragati × Kashi Chaman	-0.44	0.33	1.19	-1.89	0.11	0.27	-0.20
Kashi Satdhari × Varsha Uphar	-0.29	0.67*	0.81	11.69*	-0.64	-0.89	0.43
Kashi Satdhari × Palam Komal	1.28	-0.47	1.96*	-2.96	1.38*	2.58*	-0.25
Kashi Satdhari × Punjab Suhabani	-1.96	0.09	-0.94	-4.10	0.35	0.44	-0.48
Kashi Satdhari × Kashi Chaman	0.97	-0.28	-1.84*	-4.62	-1.09*	-2.13*	0.30
S.E. (Sij) ±	1.02	0.33	0.75	3.80	0.46	0.60	0.28
S.E. (Sij-Sjk) ±	1.45	0.47	1.06	5.37	0.65	0.86	0.40

Table 6. Pooled assessment of the specific combining ability (SCA) for 14 traits in line × tester mating fashion of okra. *significant at 5% level.

studies. The crosses developed during the study can be further utilized to improve heterosis breeding, while parental lines can aid in identifying desirable segregants for future okra breeding efforts⁹.

Limitations

Some limitations of this study are that the analysis fails to consider epistatic interactions, which are integral to the inheritance mechanisms of traits. The growth and development of okra can exhibit considerable variability from one year to the next, and the implementation of long-term studies would yield additional comprehensive insights into the stability as well as performance of hybrid varieties. The duration of this study was for 3 years, and it provides long-term trends or the stability of performance of the hybrid over several growing seasons. But the study was conducted under a single environmental condition, which may restrict the exploitation of results across diverse agro-ecological zones. Although the research identifies hybrids that are evaluated for two seasons

Cross(s)	Trait(s)						
	FD (mm)	NRPF	FW (g)	NFPP	NSPF	HSW (g)	FYPP (g)
COHF N-1 × Varsha Uphar	1.03*	0.01	-0.41	-0.15	7.39*	0.12	1.31
COHF N-1 × Palam Komal	0.26	0.02	0.02	1.13	-3.15	-0.63*	21.42*
COHF N-1 × Punjab Suhabani	-1.16*	-0.12	-0.95*	-2.23*	0.70	0.32	-43.96*
COHF N-1 × Kashi Chaman	-0.13	0.09	1.16*	1.26*	-4.94	0.19	21.22*
COHF N-2 × Varsha Uphar	0.04	0.02	-0.50	0.56	-4.63	-0.78*	2.37
COHF N-2 × Palam Komal	-0.49	0.06	-1.03*	-0.78	6.78*	-0.64*	-28.32*
COHF N-2 × Punjab Suhabani	-0.04	0.01	-0.50	-0.38	0.67	0.52*	-3.19
COHF N-2 × Kashi Chaman	0.49	-0.10	2.03*	0.60	-2.82	0.90*	29.15*
COHF N-9 × Varsha Uphar	0.20	0.02	0.52	-0.36	-1.75	1.45*	-0.34
COHF N-9 × Palam Komal	0.86*	-0.51*	-0.13	0.20	0.45	-1.03*	-7.34
COHF N-9 × Punjab Suhabani	0.24	0.83*	0.00	0.18	7.17*	0.36*	3.18
COHF N-9 × Kashi Chaman	-1.30*	-0.33*	-0.39	-0.03	-5.88	-0.78*	4.50
COHF N-11 × Varsha Uphar	0.52	0.01	0.02	2.27*	3.35	0.14	25.35*
COHF N-11 × Palam Komal	-1.28*	0.03	-0.37	0.70	1.23	-0.60*	-0.12
COHF N-11 × Punjab Suhabani	0.03	-0.01	0.30	-1.62*	-2.69	0.13	-21.36*
COHF N-11 × Kashi Chaman	0.73	-0.03	0.06	-1.36*	-1.89	0.32	-3.88
UHF-Okra-2 × Varsha Uphar	-0.16	-0.13	0.17	-2.28*	-0.50	-0.59*	-12.34
UHF-Okra-2 × Palam Komal	-0.59	-0.38*	0.01	-0.02	-3.32	0.23	-1.48
UHF-Okra-2 × Punjab Suhabani	0.73	-0.14	1.11*	1.41*	-0.73	-0.16	18.70*
UHF-Okra-2 × Kashi Chaman	0.02	0.64*	-1.28*	0.89	4.55	0.51*	-4.88
UHF-Okra-4 × Varsha Uphar	-0.19	0.10	-0.22	1.49*	-1.52	-0.56*	25.36*
UHF-Okra-4 × Palam Komal	-0.36	-0.05	0.43	-0.61	-0.05	0.29	-11.41
UHF-Okra-4 × Punjab Suhabani	0.22	0.06	0.55	-1.79*	3.83	0.38*	-10.95
UHF-Okra-4 × Kashi Chaman	0.32	-0.10	-0.76*	0.91	-2.26	-0.11	-2.99
Kashi Vibhuti × Varsha Uphar	-0.58	-0.13	0.11	1.36*	-5.85*	-0.20	1.84
Kashi Vibhuti × Palam Komal	0.65	0.67*	0.79*	-0.95	-6.70*	0.48*	16.78
Kashi Vibhuti × Punjab Suhabani	0.20	-0.17	-0.95*	-1.68*	13.73*	-0.02	-31.53*
Kashi Vibhuti × Kashi Chaman	-0.27	-0.37*	0.05	1.27*	-1.19	-0.26	12.91
Kashi Mahima × Varsha Uphar	-0.52	0.53*	0.68	0.10	-4.74	-0.50*	9.39
Kashi Mahima × Palam Komal	-0.73	-0.16	-0.81*	0.44	-1.43	0.28	-10.26
Kashi Mahima × Punjab Suhabani	1.33*	-0.12	1.56*	-1.45*	-4.41	-0.64*	6.50
Kashi Mahima × Kashi Chaman	-0.08	-0.26*	-1.43*	0.91	10.58	0.86*	-5.62
Kashi Pragati × Varsha Uphar	0.34	0.04	-0.93*	-1.47*	7.72*	0.45*	-34.35*
Kashi Pragati × Palam Komal	0.43	-0.12	1.14*	2.06*	4.57	1.09*	55.69*
Kashi Pragati × Punjab Suhabani	-0.35	0.05	0.21	1.32*	-3.72	-0.94*	15.65
Kashi Pragati × Kashi Chaman	-0.42	0.03	-0.42	-1.91*	-8.57*	-0.60*	-36.99*
Kashi Satdhari × Varsha Uphar	-0.68	-0.48*	0.57	-1.52*	0.53	0.46*	-18.59*
Kashi Satdhari × Palam Komal	1.25*	0.44*	-0.23	-2.18*	1.62	0.53*	-34.95*
Kashi Satdhari × Punjab Suhabani	-1.20*	-0.38*	-1.33*	6.24*	-14.57*	0.04	66.96*
Kashi Satdhari × Kashi Chaman	0.63	0.43*	0.98*	-2.55*	12.42*	-1.02*	-13.42
S.E. (Sij) ±	0.39	0.57	0.37	0.57	2.85	0.17	8.97
S.E. (Sij-Sjk) ±	0.55	0.80	0.53	0.80	4.04	0.24	12.69

Table 7. Pooled assessment of the SCA (specific combining ability) for 14 traits in line × tester mating fashion of okra. *significant at 5% level.

and possess desirable traits, their overall commercial feasibility as well as recognition by the farmers and markets were not assessed directly.

Conclusion

The evaluation of heterotic responses and combining ability among diverse okra genotypes highlights the potential for improving key agronomic traits through informed hybridization strategies. By identifying genetically superior crosses and parental lines, this study offers valuable insights for enhancing fruit yield and related traits. The superior parental lines identified based on their GCA can be further utilized in the hybridization during crop improvement programs. Furthermore, the best cross combinations identified from heterotic response and SCA effects can be tested across multiple locations before being released as hybrids. Focusing on these high-performing crosses allows breeding programs to improve crop productivity and efficiency. Future studies

should prioritize multi-location field trials to assess stability and adaptability across various agro-climatic zones. Additionally, incorporating molecular tools like quantitative trait loci (QTL) mapping and genome-wide association studies (GWAS) can further identify genomic regions linked to these traits, supporting sustainable agriculture and addressing food security challenges.

Data availability

The data supporting the results of this study are provided within the article and its supplementary materials. Additional raw data can be made available upon request to the corresponding authors.

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Author contributions

RP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Original draft preparation, Supervision, Writing–review & editing. AS: Supervision, Writing–review & editing, DKM: Conceptualization, Supervision, Writing–review & editing. RKB: Data curation, investigation, Methodology, Supervision, Writing–review & editing. MT: Supervision, Writing–review & editing. SG: Supervision, Writing–review & editing. MJ: Supervision, Writing–review & editing. ArM: Funding acquisition Supervision, Writing–review & editing. SaG: Supervision, Writing–review & editing. AM: Supervision, Writing–review & editing.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

The plant collection and use was in accordance with all the relevant guidelines.

Additional information

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