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Exploitation of heterosis, combining ability and gene action potential for improvement in okra (*Abelmoschus esculentus*)

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ABSTRACT

Exploitation of the heterosis, combining ability and gene action potential in okra [*Abelmoschus esculentus* (L.) Moench] serves to optimize breeding efficacy, enhance both yield and quality, and facilitate the development of disease resistant and adaptable varieties. The study was carried out during rainy (*kharif*) seasons of 2022 and 2023 at Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh to assess the combining ability and gene action potential for 14 fruit yield and related traits in 11 parental lines and their 24 crosses. The hybrid cross Neri-7×Punjab Suhawani was proven remarkably significant positive heterosis compared to both better parent (BP) and the standard check (SC) for yield and related characters. Among the parental lines, Neri-9 and Neri-11 revealed with superior general combining ability (GCA) for maximum traits. Crosses Neri-7×Punjab Suhawani followed by Neri-75×PB-5, Neri-M×Varsha Uphar, Neri-19×Punjab Suhawani, Neri-11×PB-5 and Neri-11×Varsha Uphar recorded with maximum significantly positive specific combining ability (SCA) for yield and related traits. The non-additive gene action was pronounced in governing all the traits as the ratio of general combining ability variance (σ^2GCA) and specific combining ability variance (σ^2SCA) was recorded less than one for all of the characters. Proportional contribution (in per cent) of the lines was recorded greater than the testers but it was recorded lower than line × tester for the maximum traits. The superior performing crosses Neri-7×Punjab Suhawani, Neri-75×PB-5, Neri-M×Varsha Uphar, Neri-19×Punjab Suhawani and Neri-11×PB-5 showed potential for producing F_1 hybrids and releasing as superior recombinants after conducting several location trials.

Keywords: General combiners, Non-additive gene, Recombinants, Segregants, Variance

Okra [*Abelmoschus esculentus* (L.) Moench] commonly known as lady's finger is an annual herbaceous warm season crop that belongs to the Malvaceae family within the order Malvales and considered as an amphidiploid crop with somatic chromosome number ranging from 2n=82 to 130 (Durazzo *et al.* 2019, Islam 2019 and Elkhalifa *et al.* 2021). It is a widely cultivated vegetable crop in tropical, subtropical and warm temperate regions worldwide (Dantas *et al.* 2021, Melaku *et al.* 2022 and Mohammed *et al.* 2022). In India, the annual production of okra exceeds by six million tonnes that globally holds first rank in overall production and highest export potential of okra (over 60%) (NHB 2022). Okra is grown in an area of around 544 thousand ha with 6889 thousand metric tonnes production of green fruits and having productivity of 12.28 metric tonnes ha annually in India (Statista 2023); with maximum production in Gujarat (0.92 tonnes), tailed by West Bengal (0.91 tonnes), Bihar (0.78 tonnes) and Madhya Pradesh (0.63 tonnes) (APEDA 2021). Being a multi-purpose vegetable crop grown throughout the world and it provides vitamins (A, B, and C), protein, and essential minerals abundantly. Okra is considered as an often cross-pollinated crop, with a frequency ranging from 4–19% (Fufa 2019) and is consumed for its tenderous green fruits which are botanically known as "pod".

Significant amount of variability has been observed in the yield and contributing parameters among the local cultivars as reported by Sandeep *et al.* (2022) and Yadav *et al.* (2024). As a result, the current levels of production fails to meet the demands of the rising population. Consequently, developing high yielding cultivars over the existing ones holds substantial importance as yield is the end result of interaction in between several components and there is no different gene for yield Panighel *et al.* (2022). In often cross-pollinated crops like okra considerable amount of diversification is observed that can be used for the selection of the good performing genotypes Mishra *et al.* (2021) and Sandeep *et al.* (2022). Identification and utilization of diversity in order to

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exploit the hybrid vigour for understanding the genetic constitution of several traits after evaluating the germplasm is very important Romdhane *et al.* (2020). For genetic improvement of yield and its related traits, it's necessary to select the suitable breeding methods dependent upon the general combining ability (GCA) of parents and the specific combining ability (SCA) of crosses Singh *et al.* (2021). The analysis of combining ability of the parental lines and their hybrids offers insight into the expression of additive gene action while selecting parents, whereas the specific combining ability for a specific trait in the hybrid shows the utilization of non-additive gene action and this guides for the selection of suitable breeding methods to identify desired segregants (Paul *et al.* 2017, Narkhede *et al.* 2021 and Singh *et al.* 2021). Hence, an experiment was conducted to assess heterosis, combining ability and gene action potential for improvement in okra.

MATERIALS AND METHODS

The study was carried out during rainy (*kharif*) seasons of 2022 and 2023 at Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh. Eleven parental lines were planted and crossed during the rainy season of June 21th, 2022 using a spacing of 45 cm × 15 cm. The parents consists of 8 lines (Neri-7, Neri-9, Neri-11, Neri-19, Neri-23, Neri-75, Neri-M and Neri-N) and three testers (Varsha Uphar, Pusa Bhindi-5 and Punjab Suhawani). In rainy season of June 26th, 2023, 11 parental lines and 24 (F_1's) hybrids along with the standard check P-8 were planted in randomized block design (RBD) with three replications and spacing 60 cm × 30 cm. Data were collected on 14 yield-related and contributing traits. Observations were recorded from randomly marked 10 plants from each replication.

Statistical analysis: The analysis of variance (ANOVA) was conducted for the randomized block design (RBD) following the methods outlined by Panse and Sukhatme (1985). In Line × Tester mating design proposed by Kempthorne (1957), female parent lines were crossed with each of the testers, and manual crossing was performed. The evaluation of the F_1 hybrid's performance was on the basis of heterosis over the mid-parent, better parent and standard check, followed by the approach suggested by Fonseca and Patterson (1968). The calculation of heterosis in F_1 hybrids involved determining the percentage increase or decrease relative to the better parent (BP) and standard checks (SC) was determined by the formulae proposed by Singh and Chaudhary (1977). The combining ability analysis followed the methodology outlined by Griffing (1956). Standard error is employed to assess the significance of the heterosis by conducting 't' test.

$$\text{Better parent heterosis (BPH \%)} = \frac{F_1 - BP}{BP} \times 100$$

$$\text{Standard heterosis (SH \%)} = \frac{F_1 - SC}{SC} \times 100$$

RESULTS AND DISCUSSION

A systematic examination of ANOVA (Analysis of variance) across 35 genotypes for various quantitative traits showed substantial differences among the parental lines, hybrid crosses as well as standard check. Generally, the variance resulting from the combined analysis of variance (ANOVA) for lines × testers was sub-divided into variances attributed to lines, testers, lines vs testers, crosses and parents vs crosses. The comparison between parents and crosses showed a considerable amount of variation for the yield and its contributing traits except first fruiting node, fruit diameter and number of ridges/fruit. Kumar *et al.* (2023) noticed substantial genetic diversity in okra related to yield and its component characters. The mean performance of parents, crosses and the standard check is shown in Fig. 1.

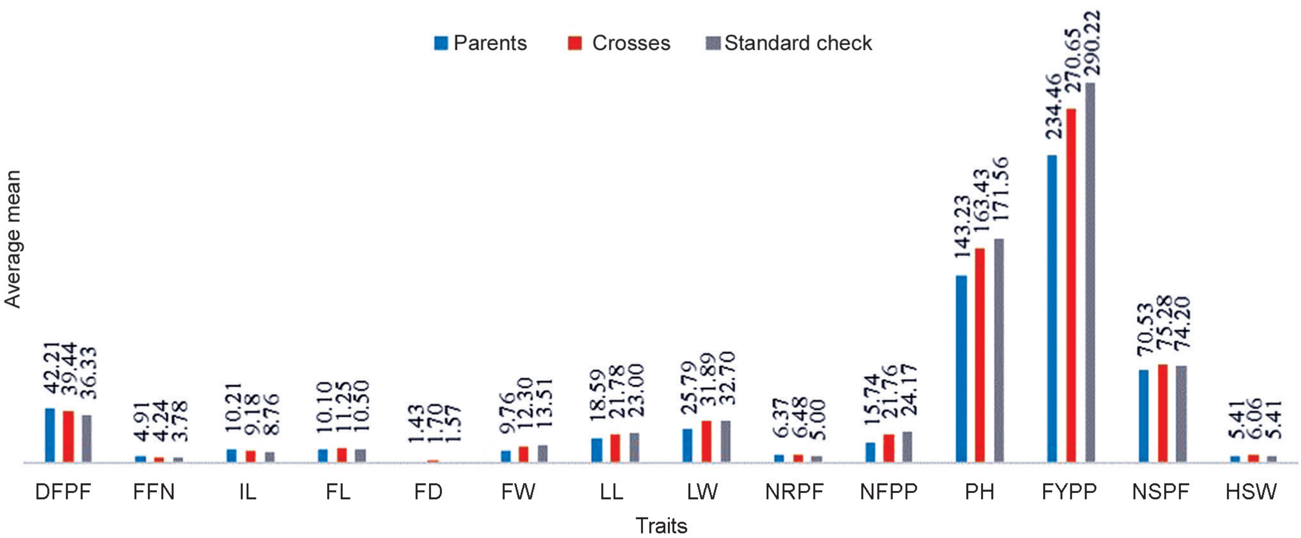

Fig. 1 Mean performance of parents, crosses and the standard check.

DFPF, Days to 50% flowering; FFN, First fruiting node; IL, Inter-nodal length; FL, Fruit length; FD, Fruit diameter; FW, Fruit weight; LL, Leaf length; LW, Leaf width; NRPF, Number of ridges/fruit; NFPP, Number of fruits/plant; PH, Height of plant; FYPP, Yield of fruits/plant; NSPF, Seed number/fruit; HSW, 100-seed weight.

Table 1 Per cent increase or decrease over better per cent (BP) and standard checks (SC) in line × tester analysis of okra

Cross	DFPF		FFN		IL		FL		FD		FW		LL	
	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check
Neri-7×Varsha Uphar	0.00	10.09*	-4.46	32.39*	-36.36*	-28.49*	9.16	14.29*	1.02	5.32	19.44*	-11.20	21.12*	-1.61
Neri-7×PB-5	-3.33	6.42	23.08	41.22*	-31.01*	-22.48*	-20.68*	-14.30*	19.15 *	23.40*	5.66	-19.41*	14.39	-8.07
Neri-7×Pb. Suhawani	-7.50*	1.83	14.29	-29.39	-5.89	5.74	32.47*	30.16*	3.14	7.66	52.02*	9.27	31.59*	1.23
Neri-9×Varsha Uphar	-6.09	-0.92	-39.02*	-11.74	-2.44	2.05	4.32	9.21	12.24	19.15*	42.67*	6.07	1.32	-17.70*
Neri-9×PB-5	0.00	5.50	0.00	14.74	-28.58*	-25.29*	-14.81*	-7.94	-14.89 *	14.89*	23.93*	-5.48	18.72*	-4.59
Neri-9×Pb. Suhawani	-7.83*	-2.75	14.29	-29.39	-17.24*	-13.43	41.84*	39.37*	16.79*	12.77	28.73*	-5.50	1.54	-21.88
Neri-11×Varsha Uphar	- 15.65*	-11.01*	-4.11	23.57	-5.13	-0.08	3.09	7.94	7.14	-2.13	20.11*	-10.71	12.76	-8.41
Neri-11×PB-5	3.48	9.17*	7.69	23.57	4.73	10.31	4.64	13.08	10.64	2.13	23.80*	-5.57	15.42	-7.25
Neri-11×Pb. Suhawani	-0.87	4.49	85.71*	14.74	-36.29*	-32.90*	31.83*	29.52*	39.09 *	0.21	9.81	-21.07*	33.62*	3.22
Neri-19×Varsha Uphar	-13.64*	4.49	11.11	76.52*	21.27*	0.42	10.86	18.63*	10.20	17.02*	44.99*	7.79	22.52*	-0.48
Neri-19×PB-5	-4.76	10.09*	-23.08	-11.74	22.83*	1.71	-3.06	4.76	2.13	-4.26	7.66	-17.88*	6.38	-14.51*
Neri-19×Pb. Suhawani	2.50	12.84*	57.14*	-2.91	-6.34	-22.44*	8.28	15.87*	21.62 *	10.64	56.49*	12.48	23.10*	-5.30
Neri-23×Varsha Uphar	-7.52*	12.84*	-50.00*	-20.56	9.80	-6.24	14.58*	19.97*	-10.20	-14.89*	29.40*	-3.80	11.83	-9.14
Neri-23×PB-5	-7.14*	7.34*	7.69	23.57	-20.00*	-31.69*	-8.93	-1.59	23.40 *	-6.38	11.90	-14.65*	18.21*	-3.96
Neri-23×Pb.Suhawani	2.50	12.84*	100	23.57	23.16*	5.17	28.27*	26.03*	52.70 *	0.00	15.48	-17.00	27.61*	3.68
Neri-75×Varsha Uphar	1.56	19.27*	-7.98	32.39*	-7.77	48.92*	-9.19	-4.92	-10.71	2.13	-13.79	-26.00*	-3.82	-11.45
Neri-75×PB-5	-1.59	13.76*	30.77*	50.04*	-25.28*	20.65*	2.91	11.21	0.40	23.40*	4.89	-9.97	9.74	1.04
Neri-75×Pb.Suhawani	5.00	15.60*	14.29	-29.39	-32.39*	9.17	10.34	8.41	5.16	24.47*	2.82	-11.74	5.49	-2.87
Neri-M×Varsha Uphar	-11.19*	9.17*	42.62*	36.80*	0.75	22.37*	7.49	12.54	-11.96	11.70	34.94*	0.32	13.59	-1.52
Neri-M×PB-5	-7.94*	6.42	33.33*	23.57	42.66*	73.26*	5.41	13.90*	-2.80	20.21*	29.37*	-1.33	-0.17	-13.45*
Neri-M×Pb. Suhawani	-3.33	13.76*	42.86	-11.74	21.64*	47.74*	16.12*	19.84*	-12.15	36.81*	23.85*	-10.98	20.81*	4.74
Neri-N×Varsha Uphar	-3.73	18.35*	-7.14	14.74	16.78*	18.60*	10.67	15.87*	17.00 *	10.64	10.32	-17.98*	12.86	-0.17
Neri-N×PB-5	-4.76	10.09*	0.00	14.74	-6.74	-5.29	8.02	16.73*	28.60 *	-4.61	0.16	-23.61	7.74	-4.88
Neri-N×Pb. Suhawani	5.00	15.60*	57.14	-2.91	34.01*	36.10*	12.86	10.89	-6.00	0.00	14.65	-17.59	9.14	-3.46

*Significant at 5% level of significance.

Table 1 *(Continued)*

Cross	LW		NRPF		NFPP		PH		FYPP		NSPF		HSW	
	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check	Better parent	Stnd. check
Neri-7×Varsha Uphar	32.38*	7.83	-21.05*	0.00	27.33*	-4.87	45.96*	17.03*	24.40*	-4.62	7.32*	2.69	-5.98	-1.17
Neri-7×PB-5	3.84	-8.41	41.18*	60.00	47.03*	-6.72	8.19	-19.17*	1.92	-15.46*	6.06*	1.48	13.96*	18.74*
Neri-7×Pb. Suhawani	41.11*	13.14	0.00	0.00	51.87*	0.52	35.79*	6.33	65.49*	23.74*	-2.19	-6.41*	-8.47*	-5.36
Neri-9×Varsha Uphar	12.39	-8.45	-19.23*	40.00*	16.28*	-13.13*	7.59	-13.73*	32.49*	3.66	3.73	5.52*	-2.11	2.90
Neri-9×PB-5	-3.36	-14.76*	-42.31*	0.00	39.30*	-11.62*	8.93	-18.59*	13.52	-5.84	5.52*	7.34*	0.65	4.87
Neri-9×Pb. Suhawani	-9.76	-27.65*	-42.31*	0.00	63.65*	8.31	14.78*	-10.13	46.69*	14.76*	-0.05	1.68	7.33	10.97*
Neri-11×Varsha Uphar	13.29	-7.72	-21.05*	0.00	32.89*	-0.72	17.88*	-3.81	26.98*	-0.10	1.75	-3.91	11.38*	17.08*
Neri-11×PB-5	1.71	-10.29	-12.02	0.00	45.62*	-7.61	15.48*	-5.77	18.21*	-1.95	11.32*	-2.48	8.46*	13.01*
Neri-11×Pb. Suhawani	26.69*	1.58	-12.03	0.00	10.00	-27.19*	32.91*	8.46	-17.86*	-35.38*	4.63*	-5.05*	5.00	8.82*
Neri-19×Varsha Uphar	28.62*	4.77	-22.22*	40.00*	-16.94	-37.95*	28.65*	8.48	6.92	-16.02*	10.25*	10.65*	-2.49	10.91*
Neri-19×PB-5	3.10	-9.06	-37.04*	13.33	17.39*	-25.52*	-9.96	-24.08*	-17.02*	-31.17*	0.50	0.86	-2.44	10.97*
Neri-19×Pb. Suhawani	9.38	-12.29	-44.44*	0.00	24.90*	-17.33*	1.42	-14.48*	33.02*	4.48	3.22	3.59	-2.43	10.97*
Neri-23×Varsha Uphar	7.32	-12.58	-21.05*	0.00	-9.56	-32.43*	-4.29	-12.23*	2.44	-8.23	-0.84	-6.36*	11.61*	17.32*
Neri-23×PB-5	10.51	-2.53	-16.67	0.00	47.30*	1.56	3.55	-5.03	8.89	-2.45	21.02*	8.49*	-7.46	-3.58
Neri-23×Pb.Suhawani	44.02*	15.48*	33.33*	60.00*	23.88*	-14.59*	-6.14	-13.93*	-10.88	-20.16*	1.95	-7.49*	-4.53	-1.29
Neri-75×Varsha Uphar	0.15	-2.50	20.00*	60.00*	-8.51	-25.54*	-12.55*	-3.16	-20.20*	-37.85*	-0.30	4.11	-6.10	-1.29
Neri-75×PB-5	17.55*	14.45	40.00*	86.67*	24.25*	1.12	-1.46	9.13	23.59*	2.51	-0.36	4.05	6.51	10.97*
Neri-75×Pb.Suhawani	3.49	0.75	50.00*	100.00*	25.30*	1.97	-15.58*	-6.15	30.24*	1.43	6.47*	11.18*	23.20*	27.37*
Neri-M×Varsha Uphar	25.30*	7.35	42.11*	80.00*	14.12*	3.42	17.73*	13.53*	35.98*	16.77*	9.09*	3.02	-6.16	-1.36
Neri-M×PB-5	-1.47	-13.09	-21.05*	0.00	-8.06	-16.69*	-5.27	-8.65	7.68	-7.52	3.65	-2.49	34.50*	40.14*
Neri-M×Pb. Suhawani	21.93*	4.47	57.89*	100.00*	-1.17	-10.44*	3.17	-0.51	4.37	-10.37	6.84*	0.51	7.33	10.97*
Neri-N×Varsha Uphar	18.09*	4.50	-21.05*	0.00	6.70	0.51	23.41	-0.97	-0.28	-7.23	0.47	0.45	23.17*	29.47*
Neri-N×PB-5	10.02	-2.64	41.18*	60.00*	-2.37	-8.04	12.55	-9.69	-14.98*	-20.91*	1.06	1.05	24.26*	29.47*
Neri-N×Pb. Suhawani	11.62	-1.22	-11.76	0.00	9.81	3.43	16.76*	-6.31	3.26	-3.94	2.23	2.22	27.01*	31.32*

*Significant at 5% level of significance. DFPF, Days to 50% flowering; FFN, First fruiting node; IL, Inter-nodal length; FL, Fruit length; FD, Fruit diameter; FW, Fruit weight; LL, Leaf length; LW, Leaf width; NRPF, Number of ridges/fruit; NFPP, Number of fruits/plant; PH, Height of plant; FYPP, Yield of fruits/plant; NSPF, Seed number/fruit; HSW, 100-seed weight.

Heterosis: Cross Neri-11×Varsha Uphar over better parent (BP) as well as standard check for days to 50 percent flowering (DFPF), Neri-23×Varsha Uphar followed by Neri-9×Varsha Uphar for first fruiting node (FFN) and Neri-7×Varsha Uphar over better parent whereas Neri-11×Punjab Suhawani over standard check for internodal length (IL) exhibited maximum significant negative heterosis (Table 1). Similar negative heterosis was reported in research conducted by Nanthakumar *et al.* (2021) and Chaudhary *et al.* (2023) for days to 50% flowering, Ranga *et al.* (2024) for first fruiting node and Pithiya *et al.* (2019) and Ranga *et al.* (2024) for internodal length. Maximum positively significant heterosis was observed in Neri-9×Punjab Suhawani over better parent (BP) and standard check (SC) for fruit length (FL), Neri-23×Punjab Suhawani over better parent and Neri-M×Punjab Suhawani for fruit diameter (FD) and Neri-9×Punjab Suhawani over better parent for number of fruits/plant (NFPF). The results are in align with Karadi and Hanchinamani (2021) and Ranga *et al.* (2024) who reported similar positive heterosis for fruit length, fruit diameter and number of fruits/plant. Fruit weight (FW) was reported with maximum positively significant heterosis over better parent for Neri-19×Punjab Suhawani. Abdelkader *et al.* (2024) concurred on these significant positive heterosis. The maximum significantly positive heterosis for fruit yield/plant (FYPP) over better parent and standard check was observed in Neri-7×Punjab Suhawani. Comparable positive heterosis results were recorded by Keerthana *et al.* (2021) and Yadav *et al.* (2023).

Recognition of general combining ability (GCA): All 8 lines and 3 testers had a strong GCA effect in the intended direction, making them effective general combiners for all characters except leaf length and leaf width (Table 2). Parental line Neri-9 followed by Neri-11 for days to 50 percent flowering, Neri-9 for first fruiting node and Neri-7 followed by Neri-9 for internodal length showed maximum significantly negative effects for GCA and indicated as effective general combiners for traits related with earliness. Comparable negative GCA effects were recorded in research conducted by Singh *et al.* (2021) and Yadav *et al.* (2023) for earliness. Parental line Punjab Suhawani for fruit length and line Neri-19 followed by Neri-9 for fruit weight reported maximum significantly positive effects for GCA. Similar positive GCA effects aligned with the findings reported by Nanthakumar *et al.* (2021) and Keerthana *et al.* (2021) for fruit length and fruit weight. Parental lines Neri-N, Neri-7, Neri-75, Neri-M and Neri-9 for number of fruits/plant whereas lines Neri-9 and Neri-7 for fruit yield/plant showed maximum significantly positive effects for GCA. Similar higher GCA effects were reported by research conducted by Keerthana *et al.* (2021) and Nanthakumar *et al.* (2021) for both of the traits.

Recognition of specific combining ability (SCA): Cross Neri-11×Varsha Uphar for days to 50% flowering, Neri-19×PB-5 followed by Neri-23×Varsha Uphar for first fruiting node and Neri-M×Varsha Uphar followed by Neri-11×Punjab Suhawani for internodal length was observed with

Table 2 Estimates of general combining ability (GCA) and specific combining ability (SCA) effects of parents for different horticultural traits in okra

Parent / Trait	DFPF	FFN	IL	FL	FD	FW	LL	LW	NRPF	NFPP	PH	FYPP	NSPF	HSW
Neri-7	-0.89*	0.09	-1.74*	-0.30	-0.02	0.25	0.57	2.17	-0.46*	1.52*	7.99	23.12*	-1.63*	-0.44*
Neri-9	-2.89*	-0.80*	-1.49*	0.07	-0.12 *	0.99*	-2.17*	-4.74*	-0.79*	0.09*	-4.39	31.74*	2.53*	-0.32*
Neri-11	-2.78*	0.31	-1.08*	0.41	0.10 *	-0.47	0.26	-0.99	-1.46*	-0.45*	14.84 *	-16.64	-3.90*	0.04
Neri-19	0.22	0.31	-1.01*	0.02	-0.07	1.32*	-0.34	-1.01	-0.57*	-4.10*	-11.50 *	-21.76*	2.66*	-0.07
Neri-23	0.89*	-0.13	-1.37*	0.20	0.06	-0.38	0.49	0.84	-0.46*	-1.25*	1.76	-10.26	-2.40*	-0.43*
Neri-75	2.78*	0.20	1.88*	-0.84*	-0.05	-0.94	0.20	2.19	2.65*	0.60*	-4.17	-13.23	3.71*	0.01
Neri-M	0.44	0.15	3.77*	0.27	-0.08	0.67	0.43	0.66	1.54*	0.50*	-2.55	18.49	-0.81	0.24*
Neri-N	2.22	-0.13	1.03*	0.17	0.18 *	-1.45*	0.56	0.87	-0.46*	2.08*	-1.97	-11.46	-0.15	0.97*
Varsha Uphar	-0.28	0.40*	0.21	-0.13	-0.01	0.28	-0.24	0.52	-0.08*	-0.93*	17.72 *	0.12	0.43	-0.16*
Pb-5	0.01	0.38*	-0.18	-0.88*	0.05	-0.44	-0.39	-1.09	-0.08*	0.19	-2.15	-10.47	0.62	0.18*
Pb. Suhawani	0.26	-0.78*	-0.03	1.01*	-0.04	0.16	0.62	0.57	0.17*	0.74*	-15.57 *	10.34	-1.05*	-0.02

Table 2 (*Continued*)

Parent \ Trait	DFPF	FFN	IL	FL	FD	FW	LL	LW	NRPF	NFPP	PH	FYPP	NSPF	HSW
Cross														
Neri-7×Varsha Uphar	1.72*	0.26	-1.39*	0.57	-0.06	-0.83	0.51	0.67	-0.92*	0.65	17.59*	-17.06	2.12	-0.12
Neri-7×PB-5	0.10	0.62	-0.47	-1.67*	0.18*	-1.22	-0.82	-3.03	2.08*	-0.92*	-25.87*	-37.95	1.03	0.61*
Neri-7×Pb. Suhawani	-1.82*	-0.88*	1.86*	1.10	-0.11	2.05*	0.31	2.36	-1.17*	0.28	8.28	55.01*	-3.15*	-0.49*
Neri-9×Varsha Uphar	-0.28	-0.51	1.04*	-0.33	0.10	0.77	-0.45	2.26	1.42*	-0.92	-8.52	-1.68	0.07	-0.02
Neri-9×PB-5	1.76*	0.51	-0.96	-1.37*	-0.01	-0.08	2.72*	1.81	-0.58*	-1.68*	1.80	-18.65	1.23	-0.26
Neri-9× Pb. Suhawani	-1.49*	0.01	-0.07	1.70*	-0.09	-0.69	-2.27*	-4.06*	-0.83*	2.59*	6.72	20.33	-1.30	0.28
Neri-11×Varsha Uphar	-4.06*	-0.29	0.44	-0.81	0.01	-0.04	-0.74	-1.26	0.08	3.62*	-15.13*	35.80*	-0.50	0.38*
Neri-11×PB-5	2.99*	-0.27	1.75*	0.49	0.03	1.37	-0.33	-0.48	0.08	0.83*	0.16	41.08*	0.37	-0.18
Neri-11×Pb. Suhawani	1.07	0.56	-2.19*	0.32	-0.04	-1.33	1.07	1.74	-0.17	-4.45*	14.97*	-76.81*	0.13	-0.20
Neri-19×Varsha Uphar	-1.39*	1.71*	0.42	0.71	0.19*	0.67	1.68	2.84	1.19*	-1.73*	22.51*	-5.29	3.74*	0.16
Neri-19×PB-5	0.32	-1.60*	0.93	0.01	-0.19*	-2.08*	-1.40	-0.06	-0.14	0.15	-14.69	-38.68*	-3.72	-0.18
Neri-19×Pb. Suhawani	1.07	-0.10	-1.34*	-0.72	0.00	1.41	-0.29	-2.78	-1.06*	1.58*	-7.82	43.97*	-0.02	0.03
Neri-23×Varsha Uphar	0.94	-1.51*	0.20	0.67	-0.08	0.81	-1.15	-4.68	-0.92*	-3.24*	-12.38	5.83	-3.82	0.87*
Neri-23×PB-5	-1.35*	0.17	-1.64*	-0.84	0.01	0.06	0.20	0.22	-0.91*	3.85*	18.62*	33.18	7.00*	-0.60*
Neri-23×Pb.Suhawani	0.40	1.34*	1.44*	0.17	0.07	-086	0.95	4.45*	1.83*	-0.60	-6.24	-39.01*	-3.18*	-0.27
Neri-75×Varsha Uphar	1.39*	0.15	1.77*	-0.90	-0.19*	-1.64*	-1.38	-2.73	-1.03*	-3.43*	-14.34	-77.17*	-2.16	-0.58*
Neri-75×PB-5	-0.90	0.84*	-0.31	1.55*	0.11	1.24	1.64	4.43*	0.31*	1.89*	25.39*	50.55*	-2.40*	-0.26
Neri-75×Pb.Suhawani	-0.49	-0.99*	-1.47*	-0.64	0.08	0.40	-0.26	-1.70	0.72*	1.54*	-11.05	26.62	4.56*	0.84*
Neri-M×Varsha Uphar	0.06	0.38	-2.44*	-0.18	-0.13	0.31	0.67	2.02	1.08*	3.67*	11.48	49.65*	1.56	-0.81*
Neri-M×PB-5	-1.24	-0.10	2.42*	0.72	-0.04	0.80	-1.92	-3.05	-2.92*	-2.31*	-7.92	-10.28	-2.73	1.09*
Neri-M×Pb. Suhawani	1.18	-0.27	0.03	-0.55	0.17*	-1.11	1.25	1.03	1.83*	-1.35*	-3.56	-39.36*	1.17	-0.28
Neri-N×Varsha Uphar	1.61*	-0.18	-0.03	0.27	0.17*	-0.04	0.85	0.88	-0.92*	1.39*	-1.20	9.93	-1.01	0.13
Neri-N×PB-5	-1.68*	-0.16	-1.72*	1.12	-0.10	-0.08	-0.08	0.16	2.08*	-1.80	2.51	-19.19	-0.77	-0.22
Neri-N×Pb. Suhawani	0.07	0.34	1.75	-1.39	-0.08	0.12	-0.76	-1.04	-1.17*	0.42	-1.30	9.26	1.78	0.09

*Significant at 5% level of significance. DFPF, Days to 50% flowering; FFN, First fruiting node; IL, Inter-nodal length; FL, Fruit length; FD, Fruit diameter; FW, Fruit weight; LL, Leaf length; LW, Leaf width; NRPF, Number of ridges/fruit; NFPP, Number of fruits/plant; PH, Height of plant; FYPP, Yield of fruits/plant; NSPF, Seed number/fruit; HSW, 100-seed weight.

the maximum significantly negative effects for SCA (Table 2). Comparable negative SCA effects were also documented by Singh *et al.* (2021), Anyaoha *et al.* (2022) and Ranga *et al.* (2024) for traits related to earliness. For earliness related traits, all the above mentioned hybrids were superior with significantly negative SCA effects. For fruit length, crosses Neri-9×Punjab Suhawani and Neri-75×PB-5 whereas for fruit weight cross Neri-7×Punjab Suhawani showed maximum positively significant effects for SCA. Similar positive SCA effects were also documented by Narkhede *et al.* (2021) and Keerthana *et al.* (2021) for both of the traits. Cross Neri-23×PB-5 followed by Neri-M×Varsha Uphar for number of fruits/plant and Neri-7×Punjab Suhawani followed by Neri-75×PB-5 for fruit yield/plant was recorded with maximum significantly positive effects for SCA. Comparable positive SCA effects were also reported by Keerthana *et al.* (2021), Narkhede *et al.* (2021) and Yadav *et al.* (2023) for above mentioned traits.

Gene action: The impact of non-additive gene action remained pronounced in governing all the characters, as the dominant variance (σ^2D) exceeded the corresponding additive variance (σ^2A). In present study, the ratio of dominance and additive variance (σ^2A/σ^2D) was less than one for all of the traits under study. For these mentioned traits the predictability ratios were less than 0.50, emphasizing the dominance of non-additive gene action in their inheritance (Table 3). The comparable variance ratio was also documented for several traits by Das *et al.* (2020) as well as Das *et al.* (2022).

Lines, testers and line × tester's proportional contribution (percent): Lines proportional contribution (percent) ranged from fruit length FL (8.77) to internodal length (IL) (64.16); for testers it was ranged from days to 50 percent flowering (DFPF) (0.79) to fruit length (FL) (38.23) and for line × tester, the range from internodal length (IL)

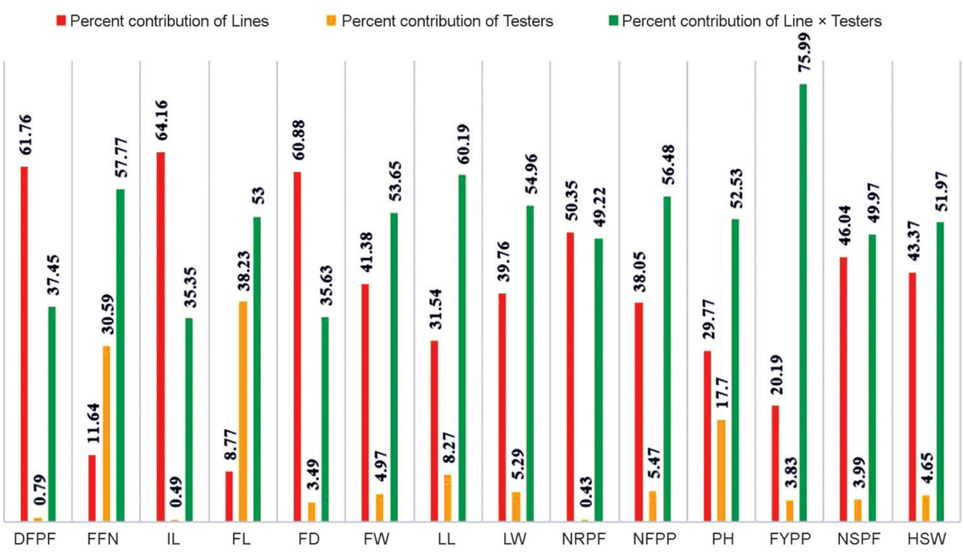

Fig. 2 Lines, testers and line × tester's proportional contribution (per cent).
DFPF, Days to 50% flowering; FFN, First fruiting node; IL, Inter-nodal length; FL, Fruit length; FD, Fruit diameter; FW, Fruit weight; LL, Leaf length; LW, Leaf width; NRPF, Number of ridges/fruit; NFPP, Number of fruits/plant; PH, Height of plant; FYPP, Yield of fruits/plant; NSPF, Seed number/fruit; HSW, 100-seed weight.

Table 3 Estimations of genetic components of variances for diverse horticultural traits

Trait	σ^2GCA (Lines)	σ^2GCA (Tester)	σ^2GCA (Average)	σ^2SCA	σ^2g (Additive)	σ^2s (Dominance)	σ^2g/σ^2s (Variance ratio)	Gene action
DFPF	3.04	-0.42	0.17	3.5	0.34	3.5	0.09	Non-additive
FFN	-0.19	0.33	0.003	0.85	0.007	0.85	0.008	Non-additive
IL	2.91	-0.37	0.16	3.09	0.33	3.09	0.106	Non-additive
FL	-0.32	0.72	0.01	1.08	0.02	1.08	0.01	Non-additive
FD	0.01	0.00	0.00	0.01	0.00	0.01	0.00	Non-additive
FW	0.33	-0.08	0.01	1.2	0.03	1.29	0.02	Non-additive
LL	0.03	-0.01	0.00	1.19	0.00	1.19	0.00	Non-additive
LW	1.58	-0.43	0.07	7.05	0.15	7.05	0.02	Non-additive
NRPF	0.95	-0.32	0.04	2.73	0.08	2.73	0.02	Non-additive
NFPP	0.99	-0.34	0.04	8.44	0.09	8.44	0.01	Non-additive
PH	13.13	50.14	3.23	244.96	6.47	244.96	0.02	Non-additive
FYPP	-383.75	-198.77	-33.75	2170.89	-67.50	2170.89	0.03	Non-additive
NSPF	3.36	-0.66	0.18	10.65	0.36	10.65	0.03	Non-additive
HSW	0.08	-0.01	0.35	0.35	0.009	0.35	0.02	Non-additive

DFPF, Days to 50% flowering; FFN, First fruiting node; IL, Inter-nodal length; FL, Fruit length; FD, Fruit diameter; FW, Fruit weight; LL, Leaf length; LW, Leaf width; NRPF, Number of ridges/fruit; NFPP, Number of fruits/plant; PH, Height of plant; FYPP, Yield of fruits/plant; NSPF, Seed number/fruit; HSW, 100-seed weight.

(35.35) to fruit yield/plant (FYPP) (75.99) was observed, respectively (Fig. 2). Proportional contribution (percent) of the lines was observed higher than the testers with exception for first fruiting node (FFN) but it was recorded lower than line × tester for the maximum traits except days to 50% flowering (DFPF), internodal length (IL), fruit diameter (FD) and number of ridges/fruit (NRPF). For these four traits, the contribution of lines recorded higher than that of the contribution from the interaction in between line × tester. Higher impact of lines on traits were also reported by Das *et al.* (2020) and Ranga *et al.* (2024).

The analysis of heterosis, combining ability and gene action has successfully identified promising parents and crosses that provide the development of a cohesive strategy for improvement of okra. The main objective of this study was to assess the significance of heterosis, general combining ability as well as specific combining ability effects and gene action in okra, with the aim of creating new F_1 hybrids having higher yields. The study suggests that parental lines Neri-9 and Neri-7 was observed to be good general combiners whereas crosses Neri-7×Punjab Suhawani, Neri-75×PB-5, Neri-M×Varsha Uphar, Neri-19×Punjab Suhawani and Neri-11×PB-5 showed maximum significant SCA effects and heterosis for most of the characters. The prevalence of non-additive gene action in trait inheritance suggests that heterosis breeding will be favorable and lead to rapid improvements in okra. Therefore, these crosses may be exploited to enhance heterosis breeding and parental lines can facilitate the selection of desirable segregants in future okra breeding programmes.

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