Exploitation of heterosis and combining ability potential for improvement in okra (Abelmoschus esculentus L.)

Aman Deep Ranga
aman_ranga94@yahoo.com

Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Amit Vikram
Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Ramesh Kumar
Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Rajesh K Dogra
Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Rajnish Sharma
Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Hem Raj Sharma
Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Article

Keywords: Combining ability, heterobeltiosis, heterosis, hybrids, standard check

Posted Date: March 29th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4183854/v1

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on October 19th, 2024. See the published version at https://doi.org/10.1038/s41598-024-75764-9.

Abstract

The experiment was conducted from 2021 to 2022 at Experimental Farm and Quality Analysis Laboratory, Department of Vegetable Science, College of Horticulture, Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh, India to estimate heterosis and combining ability in Okra (*Abelmoschus esculentus* L.). Okra is an often cross-pollinated crop; therefore, exploiting heterosis is advantageous. The experimental material consisted of an F_1 population of 30 crosses obtained from of 10 parental lines crossed with three testers in a Line × Tester mating design, plus a standard check (Punjab-8). Estimates of heterosis (heterobeltiosis and standard heterosis) of the cross combinations UHFO-6 × Pusa Bhindi-5, UHFO-6 × Arka Anamika and UHFO-9 × Arka Anamika were high for majority of the horticultural traits. Significant combining ability effects (GCA and SCA) were resulted from UHFO-6 and UHFO-9 among the parents and UHFO-2 × Pusa Bhindi-5, UHFO-10 × Hisar Unnat and UHFO-2 × Arka Anamika among cross combination. In future, after multi-location trials, these parents and crosses can be released to replace existing okra cultivars (hybrids/varieties).

Introduction

Abelmoschus esculentus (L.) Moench often known as okra, is a popular vegetable crop farmed across the nation throughout the summer and rainy season. Because of its ease of cultivation, consistent output, year-round export potential, high nutritional value, vast tolerance to different moisture conditions, and resilience to diseases and pests, it has become one of the most popular vegetable crops in the tropics. Okra is indeed an often-cross-pollinated vegetable crop with the somatic chromosomal number of 2n = 130. It is most likely an amphidiploid of *Abelmoschus tuberculatus* (2n = 58) with a species unknown (2n = 72) (Datta and Naug 1968)[1].

In 2021, India's annual okra output is expected to be 6.81 million MT from 0.55 million hectares of land, with a productivity of 12.38 tonnes/ha (Agricultural Statistics at a Glance, 2022)[2]. Gujarat produced 1.09 million MT from an area of 0.08 million hectare became the leading state for producing okra followed by West Bengal (National Horticulture Board 2022)[3]. Its plump, delicate, and green fruits are highly valued. Okra fruits are high in calcium and provide important nutrients and minerals to tropical diets. The tender fruits are cooked like a vegetable, generally fresh and sometimes dried in the sun or preserved (Thamburaj and Singh 2018)[4].

Due to low yielding cultivars and the prevalence of different pests and diseases, the yield potential is quite low (Ranga et al. 2024)[5]. By speeding productivity growth, hybrid breeding has assisted in breaking through yield constraints. Furthermore, exploitation of hybrid vigour, comprehending the genetics of different traits, and quality enhancement with a focus on the export market must be prioritized in crop improvement programmes (Labroo et al. 2021)[6]. The most popular method of choosing parents based only on their per se performance is not always effective. The whole genetic transformation and prepotency of possible parents must be taken into consideration when choosing the ideal parents for hybridization (Yadav et al., 2023)[7]. Any crop's heterosis and combining ability studies are necessary to give sufficient information on the ideal parents and crosses for additional genetic advancement. The current study aimed to evaluate heterosis and combining ability for both morphological and biochemical traits, as well as to discover superior hybrids with the following objectives:

1. To estimate mean performance, nature and magnitude of heterosis for yield and yield contributing characteristics
2. To study combining ability for important horticultural characteristics

Results

Analysis of Variance

A thorough investigation of the analysis of variance among 43 genotypes for various quantitative traits revealed extremely significant variations between the parents, crosses, and the standard check. The overall variance from the combined ANOVA of line × tester was divided into variances due to lines, testers, lines vs. testers, crosses, and parents vs. crosses. Parents and crosses demonstrated significance variations in every trait under study (Supplementary Table 1). Figure 1 depicts the average mean performance of parents, crosses, and controls.

Heterosis studies

Standard heterosis

It is the superiority of F_1 compared to the high yielding commercial variety or cultivar in a particular location. Standard heterosis is an important measure in plant breeding, indicating the potential improvement in performance compared to existing commercially successful varieties. Data pertaining to standard heterosis is depicted in Table 1–2 and Fig. 2. None of the hybrids showed negative significant heterosis from days until 50 per cent flowering, indicating that none of the hybrids exhibited a significant delay in flowering compared to the high-yielding commercial variety. Three crosses showed considerable minimal heterosis for the first flowering node. Three crosses showed considerable positive heterosis in plant height. With three crosses, there was considerable minimal heterosis in inter-nodal length. With three crosses, the number of primary branches per plant showed considerable positive heterosis. Three crosses showed positive significant heterosis in pod length, and six crosses revealed positive substantial heterosis in pod diameter, indicating improvements in pod size compared to the commercial variety. With sixteen crosses, there was positive significant heterosis in the number of pods per plant. Three crosses showed positive significant heterosis in average pod weight, and twelve crosses showed considerable positive heterosis in pod yield per plant, indicating improvements in individual pod weight and overall yield compared to the commercial variety. For four crosses, the days to first picking showed the least significant heterosis. For harvest duration, nine crosses demonstrated considerable positive heterosis. Three crosses demonstrated considerable positive heterosis for the number of seeds per pod, and three crosses demonstrated considerable positive heterosis for hundred seed weight, suggesting improvements in both seed quantity and individual seed weight compared to the commercial variety. Three crosses demonstrated considerable positive heterosis for average pod dry weight. Nineteen crosses exhibited strong positive heterosis for total sugar. For total polyphenol content, twenty eight F_1 hybrids showed positive significant heterosis. Fourteen crosses showed positive significant heterosis for total protein and fifteen for total nitrogen. For mucilage content, 22 F_1 hybrids showed positive significant heterosis.

Table 1
Estimation of standard heterosis (%) in line × tester mating design of okra for different traits

Hybrids \ Traits	DF	FF	PH	IL	BP	PL	PD	PP	PW	PYP
UHFO-2 × AA	11.90*	-8.33	-12.27*	14.46	1.89	16.33*	0.13	46.94*	18.69*	73.53*
UHFO-2 × PB	16.67*	-2.75	-9.25*	27.82*	-42.64*	10.88	23.24*	56.26*	42.58*	81.38*
UHFO-2 × HU	9.26	38.89*	-4.33	29.58*	-5.66*	-16.31*	7.83*	35.34*	-25.71*	0.68
UHFO-3 × AA	0.00	-8.33	3.14	6.50	5.28*	17.37*	15.54*	22.13	33.13*	41.97*
UHFO-3 × PB	-3.97	41.67	6.43*	-13.83	1.89	21.46*	7.83*	0.02	11.78	11.89
UHFO-3 × HU	13.49*	19.42	9.89*	2.53	-12.08*	23.47*	7.83*	-4.49	-2.49	-6.32
UHFO-4 × AA	7.4	-8.33	7.18*	18.52*	-5.66*	30.61*	15.54*	7.99	44.17*	16.26
UHFO-4 × PB	21.43*	11.08	8.18*	-0.49	0.75	7.14	-7.57*	47.45*	-16.14*	23.69
UHFO-4 × HU	21.16*	-8.33	11.24*	-2.35	-18.11*	16.33*	15.54*	3.11	18.80*	10.43
UHFO-5 × AA	7.67	16.67	-12.79*	-20.94*	-12.08*	0.00	7.83*	37.49*	-13.76	18.61
UHFO-5 × PB	3.44	-13.92	-9.28*	-17.29*	-5.66*	7.14	-7.57*	2.28	-5.78	-3.58
UHFO-5 × HU	-0.79	33.33*	-2.70	-8.67	-32.45*	17.35*	-7.57*	12.63	-28.26*	-19.19
UHFO-6 × AA	5.56	-8.33	-16.39*	-11.40	-32.08*	27.55*	15.54*	59.54*	8.66	127.73*
UHFO-6 × PB	18.25*	-8.33	-10.70*	-16.25*	-18.11*	41.84*	15.54*	67.49*	-8.49	129.29*
UHFO-6 × HU	11.37	47.25*	-7.99*	-3.00	-35.85*	47.96*	23.24*	39.96*	36.81*	107.45*
UHFO-7 × AA	-2.38	13.89	5.83	-4.17	-12.08*	-4.08	7.83*	29.17*	-26.73*	33.37
UHFO-7 × PB	-3.7	44.42*	8.96*	-13.35	5.28*	47.96*	23.24*	1.61	29.45*	13.26
UHFO-7 × HU	15.61*	11.08	15.38*	4.43	-4.91*	2.04	15.54*	20.44	2.43	23.31
UHFO-8 × AA	-9.52	5.58	-24.76*	-33.99*	-4.91*	15.31*	23.24*	25.00	-4.19	19.69
UHFO-8 × PB	15.87*	41.67*	-19.93*	-27.78*	6.79*	-3.06	7.83*	39.87*	-11.78	39.70*
UHFO-8 × HU	9.52	47.25*	-15.89*	-28.43*	-12.08*	12.24*	7.83*	-8.11	-6.06	0.58
UHFO-9 × AA	14.29*	33.33*	19.32*	40.35*	-5.66*	5.10	0.13	43.75*	1.53	46.05*
UHFO-9 × PB	-3.17	16.67	23.55*	58.95*	-18.11*	32.65*	30.94*	40.65*	51.64*	33.17
UHFO-9 × HU	14.02*	22.25*	29.63*	51.45*	-24.53*	-8.16	7.83*	44.09*	-3.57	38.98*
UHFO-10 × AA	14.29*	44.42*	37.74*	54.43*	-32.45*	7.14	15.54*	8.17	0.91	9.28
UHFO-10 × PB	-1.59	25.00*	42.50*	8.46	-35.85*	-8.16	0.13	11.14	-10.82	-1.23
UHFO-10 × HU	19.05*	55.58*	44.11*	64.95*	-30.94*	8.16	7.83*	21.57	5.95	27.60
UHFO-14 × AA	-2.38	-8.33	24.58*	21.83*	-12.08*	9.18	7.83*	31.26*	-13.14	47.84*
UHFO-14 × PB	3.97	-5.58	23.20*	47.26*	0.75	2.04	23.24*	34.34*	-4.02	37.62*
UHFO-14 × HU	22.22*	-16.67	28.82*	52.88*	-35.85*	-8.16	0.13	34.96*	-28.77*	39.97*

*Significant at 5% level of significance.

Where, AA: Arka Anamika, PB: Pusa Bhindi-5, HU: Hisar Unnat, DF: days to 50 per cent flowering, FF: first flowering node, PH: plant height, IL: inter-nodal distance, BP: number of primary branches per plant, PL: pod length, PD: pod diameter, PP: number of pods per plant, PW: average pod weight and PYP: pod yield per plant

Table 2
Estimation of standard heterosis (%) in line × tester mating design of okra for different traits

Hybrids \ Traits	**FP**	**HD**	**SP**	**SW**	**DW**	**TS**	**TPP**	**TP**	**TN**	**MC**
UHFO-2 × AA	**13.67***	**-9.60***	-2.17	**-22.98***	-5.84	**32.14***	**188.19***	**14.23***	**14.23***	3.86
UHFO-2 × PB	8.63	**10.07***	-3.85	**-14.74***	**27.59***	**44.64***	**94.51***	**47.84***	**47.84***	**36.84***
UHFO-2 × HU	3.60	5.35	**6.39***	**-21.71***	3.13	**-36.31***	**7.59***	**53.92***	**53.92***	**-64.91***
UHFO-3 × AA	**9.35***	6.99	3.61	**-12.68***	**65.72***	**20.83***	**100.42***	**-18.56***	**-18.56***	**24.56***
UHFO-3 × PB	**14.39***	5.36	**14.57***	**7.13***	**43.01***	**54.17***	**138.82***	**20.82***	**20.82***	**53.68***
UHFO-3 × HU	**15.83***	-0.93	**11.43***	**-27.10***	**10.96***	**108.93***	**97.47***	**-11.44***	**-11.44***	**57.89***
UHFO-4 × AA	**11.51***	**-7.82***	-2.22	**18.70***	**34.10***	**92.26***	**359.49***	**-8.04***	**-8.04***	**-6.67***
UHFO-4 × PB	**19.42***	4.77	0.39	**-19.49***	**10.90***	**-8.93***	**60.34***	**-7.84***	**-7.84***	**-34.39***
UHFO-4 × HU	**17.99***	-1.78	-3.33	**-15.85***	**38.43***	**-25.60***	**30.80***	**46.49***	**46.49***	**44.91***
UHFO-5 × AA	**12.94***	-3.45	**-7.54***	**-22.03***	5.00	**130.36***	**70.04***	**-8.45***	**-8.45***	**51.93***
UHFO-5 × PB	8.63	**-8.91***	**-13.92***	**-15.21***	7.47	**116.67***	**73.00***	**49.28***	**49.28***	**12.28***
UHFO-5 × HU	**23.02***	**-14.89***	**-10.49***	**-19.33***	**-26.08***	**188.69***	**16.46***	**-42.16***	**-42.16***	**42.11***
UHFO-6 × AA	-1.44	6.09	**7.39***	**-11.09***	**39.70***	**84.52***	**81.01***	**47.73***	**47.73***	**76.14***
UHFO-6 × PB	-5.76	**16.17***	**14.77***	**12.52***	**9.40***	**41.67***	**156.96***	**-5.46***	**-5.46***	**58.95***
UHFO-6 × HU	-3.60	**8.93***	**7.26***	-1.43	**47.95***	**44.64***	**13.50***	**61.96***	**61.96***	**7.37***
UHFO-7 × AA	3.60	2.74	2.70	**5.07***	**-16.02***	**-14.29***	**-12.66***	-3.51*	-3.51*	**51.93***
UHFO-7 × PB	2.16	**9.01***	**6.39***	**-10.46***	**25.66***	**25.00***	**110.13***	**-31.03***	**-31.03***	**-24.91***
UHFO-7 × HU	-2.16	3.82	3.61	-5.23*	**15.00***	**114.29***	**188.19***	**-30.00***	**-30.00***	**35.79***
UHFO-8 × AA	**17.27***	**9.39***	-3.77	**-6.81***	**-22.17***	**72.02***	**131.65***	**12.27***	**12.27***	**50.53***
UHFO-8 × PB	**17.99***	-0.69	4.68	**-14.10***	**17.95***	**-11.31***	**48.52***	**-27.01***	**-27.01***	**11.93***
UHFO-8 × HU	**10.79***	2.27	**11.21***	-0.48	4.76	**120.24***	**361.60***	**-46.60***	**-46.60***	**73.33***
UHFO-9 × AA	-4.32	**16.35***	0.01	**-14.26***	**20.06***	**96.43***	**21.10***	1.65*	1.65*	**-6.32***
UHFO-9 × PB	0.00	**16.59***	3.23	**5.23***	**40.84***	**54.76***	**109.28***	**7.84***	**7.84***	**13.68***
UHFO-9 ×	**12.23***	-0.89	-2.33	**-7.61***	**7.41***	**-34.52***	**86.92***	**-10.72***	**-10.72***	-2.11

*Significant at 5% level of significance.

Where, AA: Arka Anamika, PB: Pusa Bhindi-5, HU: Hisar Unnat, FP: days to first picking, HD: harvest duration, SP: number of seeds per pod, SW: hundred seed weight, DW: average dry weight of pod. TS: total sugars, TPP: total polyphenol, TP: total protein, TN: total nitrogen and MC: mucilage content.

Hybrids \ Traits	FP	HD	SP	SW	DW	TS	TPP	TP	TN	MC
HU										
UHFO-10 × AA	**15.10***	4.83	2.55	**-29.64***	**9.64***	**-16.67***	**562.03***	**-20.93***	**-20.93***	**45.61***
UHFO-10 × PB	**20.86***	5.41	2.14	**-8.40***	6.20	**16.07***	**314.77***	**63.71***	**63.71***	**45.26***
UHFO-10 × HU	**23.74***	-2.07	-4.13	**-6.18***	**24.76***	0.00	**62.03***	**43.09***	**43.09***	**20.00***
UHFO-14 × AA	0.72	**12.39***	**10.17***	**-20.60***	**-19.64***	**-18.45***	**118.14***	**-9.90***	**-9.90***	**-20.00***
UHFO-14 × PB	6.47	**14.48***	**12.60***	**-15.85***	-3.01	**-29.17***	**-25.32***	**9.79***	**9.79***	**9.82***
UHFO-14 × HU	**15.11***	3.40	**8.11***	**-10.62***	**10.72***	**-11.31***	**40.08***	**18.66***	**18.66***	**22.11***

*Significant at 5% level of significance.

Where, AA: Arka Anamika, PB: Pusa Bhindi-5, HU: Hisar Unnat, FP: days to first picking, HD: harvest duration, SP: number of seeds per pod, SW: hundred seed weight, DW: average dry weight of pod. TS: total sugars, TPP: total polyphenol, TP: total protein, TN: total nitrogen and MC: mucilage content.

Table 3
Estimation of heterobeltiosis (%) in line × tester mating design of okra for different traits

Hybrids \ Traits	DF	FF	PH	IL	BP	PL	PD	PP	PW	PYP
UHFO-2 × AA	22.26*	0.00	-0.46	75.44*	15.88*	-10.24*	-18.66*	25.85*	14.04*	42.25*
UHFO-2 × PB	26.72*	6.09	-1.73	48.63*	-49.33*	-14.44*	6.58*	33.84*	37.00*	48.69*
UHFO-2 × HU	18.68*	51.52*	-6.19	4.93	25.00*	-35.42*	-6.57*	-5.85	-35.11*	-38.86*
UHFO-3 × AA	9.25	-5.72	17.02*	63.24*	11.60*	-0.84	-6.25*	6.03	21.69*	12.63
UHFO-3 × PB	-4.72	45.70*	15.24*	0.20	-10.00*	2.61	-12.50*	-13.17	2.17	-11.23
UHFO-3 × HU	19.50*	22.82*	9.88*	4.98	-6.80*	4.31	-12.50*	-33.56*	-14.84*	-43.11*
UHFO-4 × AA	17.34*	-17.50	4.32	81.66*	-10.39*	28.01*	-6.15*	-15.76	48.20*	-6.76
UHFO-4 × PB	20.47*	-4.79	5.30	15.71	-11.00*	-7.90	-20.06*	15.03	-16.04*	-0.81
UHFO-4 × HU	27.57*	-34.00*	8.28*	-15.93*	-22.22*	8.57	7.14*	-28.27*	3.76	-32.94*
UHFO-5 × AA	17.64*	5.00	-1.06	21.18	0.00	-1.99	-12.40*	34.46*	-3.97	54.79*
UHFO-5 × PB	2.63	-26.21*	-1.77	-1.45	-16.67*	-7.90	-20.06*	0.03	-5.67	21.95
UHFO-5 × HU	4.45	-11.11	-4.59	8.81	-10.50*	9.52	-14.29*	-21.65*	-37.34*	-50.93*
UHFO-6 × AA	15.32	-17.50*	-5.14	35.81*	-22.75*	-8.73*	-6.15*	5.09	-24.33*	4.54
UHFO-6 × PB	24.17*	-21.43	-3.31	-2.61	-27.67*	1.49	-0.08	10.33	-36.28*	5.25
UHFO-6 × HU	17.26*	0.00	-9.78*	8.24	-15.00*	5.87	14.29*	-7.81	-4.73	-4.77
UHFO-7 × AA	6.65	2.50	-3.48	46.88*	-19.66*	-5.99	-12.40*	21.57	-29.52*	20.78
UHFO-7 × PB	2.83	23.79*	-0.63	0.75	-7.00*	27.19*	6.58*	-4.37	24.51*	2.57
UHFO-7 × HU	23.45*	-6.98	5.23	38.78*	-13.10*	-4.76	7.14*	-16.22	-10.53	-25.12*
UHFO-8 × AA	-1.15	15.17	-14.63*	3.59	4.13	6.58	0.11	-2.96	-9.90	-12.64
UHFO-8 × PB	14.96*	54.55*	-13.30*	13.34	-5.67*	-16.67*	-6.74*	8.59	-17.04*	1.97
UHFO-8 × HU	15.32*	60.64*	-17.52*	12.31	-3.72	3.76	0.00	-36.07*	-17.95*	-38.92*
UHFO-9 × AA	24.86*	45.45*	-4.21	115.12*	7.30*	-10.44*	-18.66*	68.25*	10.41	90.59*
UHFO-9 × PB	-3.94	27.27*	-0.81	84.83*	-27.67*	13.04*	13.25*	77.62*	51.81*	68.44*
UHFO-9 ×	20.05*	33.36*	4.07	11.70*	-6.10*	-21.74*	0.00	0.23	-15.78*	-15.60

*Significant at 5% level of significance.

Where, AA: Arka Anamika, PB: Pusa Bhindi-5, HU: Hisar Unnat, DF: days to 50 per cent flowering, FF: first flowering node, PH: plant height, IL: inter-nodal distance, BP: number of primary branches per plant, PL: pod length, PD: pod diameter, PP: number of pods per plant, PW: average pod weight and PYP: pod yield per plant

Hybrids \ Traits	DF	FF	PH	IL	BP	PL	PD	PP	PW	PYP
HU										
UHFO-10 × AA	**24.86***	**92.56***	-1.41	**136.71***	**-23.18***	5.01	**-6.15***	**-24.23***	1.83	-22.69
UHFO-10 × PB	-2.36	**66.67***	2.00	**26.12***	**-43.33***	**-21.05***	**-13.40***	**-22.14***	-10.00	**-46.62***
UHFO-10 × HU	**25.34***	**107.44***	3.15	**21.66***	**-8.50***	0.95	0.00	-15.43	-7.47	-8.53
UHFO-14 × AA	6.65	6.45	-1.16	**86.74***	0.00	-2.73	**-12.40***	14.08	**-29.70***	4.37
UHFO-14 × PB	3.15	9.65	-2.26	**71.24***	**-11.00***	**-12.28***	6.58	16.75	**-22.32***	-19.10
UHFO-14 × HU	**28.69***	-3.23	2.20	**12.76***	**-15.00***	**-18.18***	**-7.14***	-6.11	**-42.35***	85.00*
*Significant at 5% level of significance.										
Where, AA: Arka Anamika, PB: Pusa Bhindi-5, HU: Hisar Unnat, DF: days to 50 per cent flowering, FF: first flowering node, PH: plant height, IL: inter-nodal distance, BP: number of primary branches per plant, PL: pod length, PD: pod diameter, PP: number of pods per plant, PW: average pod weight and PYP: pod yield per plant										

Table 4
Estimation of heterobeltiosis heterosis (%) in line × tester mating design of okra for different traits

Hybrids \ Traits	FP	HD	SP	SW	DW	TS	TPP	TP	TN	MC
UHFO-2 × AA	**20.60***	**-21.17***	1.58	**-26.48***	**-34.88***	**-18.38***	**45.01***	**-13.77***	**-13.77***	2.07
UHFO-2 × PB	5.59	-4.01	**-10.65***	**-22.37***	**-11.75***	**-10.66***	-2.12	**11.60***	**11.60***	-2.50
UHFO-2 × HU	9.09	**-8.12***	-0.22	**-22.57***	**-28.67***	**-60.66***	**-45.86***	**16.19***	**16.19***	**-65.52***
UHFO-3 × AA	**16.03***	**-6.35***	-2.44	**-16.64***	**80.39***	**-33.00***	**10.72***	**-37.25***	**-37.25***	**-30.39***
UHFO-3 × PB	6.00	-4.63	**6.47***	-2.45	**20.88***	**-14.52***	**28.05***	**-6.91***	**-6.91***	**-14.12***
UHFO-3 × HU	**21.97***	**-8.59***	4.50	**-29.98***	**-16.65***	**15.84***	**30.00***	**-31.77***	**-31.77***	**-11.76***
UHFO-4 × AA	**18.32***	**-19.32***	**-5.80***	**13.31***	**45.97***	**53.81***	**-12.81***	**-6.20***	**-6.20***	**-14.19***
UHFO-4 × PB	**10.67***	-5.17	**-6.71***	**-26.70***	**-6.26***	**-27.14***	**-69.58***	**-5.80***	**-5.89***	**-53.25***
UHFO-4 × HU	**24.24***	**-9.37***	**-9.33***	**-16.77***	3.98	**-40.48***	**-75.18***	**44.70***	**44.70***	**33.23***
UHFO-5 × AA	**19.83***	**-15.50***	-0.24	**-25.57***	3.75	**55.42***	**-17.42***	**-6.62***	**-6.53***	**106.19***
UHFO-5 × PB	0.67	**-17.55***	**-20.01***	**-22.80***	**-9.16***	**46.18***	**-15.98***	**62.33***	**104.12***	**-20.00***
UHFO-5 × HU	**29.55***	**-21.46***	**-16.05***	**-20.22***	**-44.48***	**94.78***	**-43.44***	**-42.87***	**-42.83***	**153.13***
UHFO-6 × AA	6.20	**-9.47***	**-6.94***	**-15.13***	**-18.35***	**30.80***	0.00	**46.67***	**46.50***	**109.17***
UHFO-6 × PB	-4.39	-0.88	-0.54	2.45	**-36.06***	0.42	**37.78***	**-6.14***	**-6.25***	**13.25***
UHFO-6 × HU	1.52	**-7.05***	**-7.05***	-2.51	**-13.52***	**2.53***	**-25.28***	**59.98***	**60.10***	**27.50***
UHFO-7 × AA	**11.63***	**-10.08***	4.29	0.30	**-15.00***	**-68.00***	**-86.29***	**-9.21***	**-9.21***	**-11.63***
UHFO-7 × PB	**10.08***	-1.33	-1.13	**-18.47***	**6.43***	**-53.33***	**-67.02***	**-35.11***	**-35.11***	**-56.33***
UHFO-7 × HU	5.43	-6.02	-2.83	**-6.27***	**-14.01***	**-20.00***	**-54.77***	**-34.14***	**-34.14***	**-21.02***
UHFO-8 × AA	**24.43***	-4.25	-4.60	**-11.04***	**-47.90***	**104.96***	**-10.15***	**14.51***	**14.51***	**104.29***
UHFO-8 × PB	**9.33***	**-10.11***	-2.72	**-21.79***	**-21.05***	**-19.02***	**-42.39***	**-15.71***	**-15.78***	**59.50***
UHFO-8 × HU	**16.67***	-5.63	4.30	-1.57	**-29.88***	**85.00***	**79.05***	**-47.25***	**-47.25***	**160.00***
UHFO-9 × AA	1.53	1.83	-1.42	**-18.15***	**13.24***	**3.12***	**-33.10***	**3.68***	**3.68***	**-19.09***
UHFO-9 × PB	-4.80	5.53	-4.07	**-4.18***	**19.29***	**-18.75***	**12.22***	**47.53***	**47.53***	**62.00***
UHFO-9 ×	**18.18***	**-9.63***	**-8.40***	**-8.62***	**-19.68***	**-65.63***	**23.06***	**-11.81***	**-11.81***	**-15.45***

*Significant at 5% level of significance.

Where, AA: Arka Anamika, PB: Pusa Bhindi-5, HU: Hisar Unnat, FP: days to first picking, HD: harvest duration, SP: number of seeds per pod, SW: hundred seed weight, DW: average dry weight of pod. TS: total sugars, TPP: total polyphenol, TP: total protein, TN: total nitrogen and MC: mucilage content.

Hybrids \ Traits	FP	HD	SP	SW	DW	TS	TPP	TP	TN	MC
HU										
UHFO-10 × AA	**22.13***	**-8.24***	2.21	**-32.83***	**-6.19***	-0.71	**79.93***	**-38.20***	**-38.20***	**-27.19***
UHFO-10 × PB	**12.00***	-4.59	-5.09	**-16.59***	**-10.05***	**5.98***	**12.73***	**27.96***	**27.96***	**-27.37***
UHFO-10 × HU	**30.30***	**-9.64***	**-10.09***	**-7.21***	**-6.71***	**-16.00***	**-55.96***	**11.85***	**11.85***	**-40.00***
UHFO-14 × AA	6.87	-3.05	-3.53	**-24.21***	**-48.29***	**-2.84**	**20.51***	**-8.10***	**-8.10***	**-43.00***
UHFO-14 × PB	6.48	-1.25	-1.41	**-23.38***	**-37.60***	**-35.33***	**-59.95***	**35.50***	**35.24***	**-21.75***
UHFO-14 × HU	**21.21***	**-10.80***	**-5.34***	**-11.60***	**-28.76***	**-25.50***	**-7.78***	**17.21***	**17.21***	**-13.00***

*Significant at 5% level of significance.

Where, AA: Arka Anamika, PB: Pusa Bhindi-5, HU: Hisar Unnat, FP: days to first picking, HD: harvest duration, SP: number of seeds per pod, SW: hundred seed weight, DW: average dry weight of pod. TS: total sugars, TPP: total polyphenol, TP: total protein, TN: total nitrogen and MC: mucilage content.

Heterobeltiosis

It is the superiority of the F_1 hybrid over the better parent. It is also called as "Heterobeltiosis". Data pertaining to heterobeltiosis is depicted in Supplementary Table 3–4 and Fig. 2. None of the hybrids showed substantial negative heterosis from days until 50 per cent flowering. Twelve crosses showed substantial heterosis at the first flowering node, indicating enhanced early flowering in these hybrids. Three crosses showed considerable positive heterosis in plant height. Only one cross demonstrated considerable negative heterosis in inter-nodal length. With three crosses, the number of primary branches per plant showed considerable positive heterosis. Three crosses showed positive significant heterosis in pod length and pod diameter, indicating enhanced pod size in these hybrids. Five crosses demonstrated positive significant heterosis in the number of pods per plant. For three crosses, the average pod weight showed positive significant heterosis, and six crosses showed considerable positive heterosis in pod yield per plant, indicating increased individual pod weight and overall yield in these hybrids. For three crosses, the days to first picking showed the least significant heterosis. There was no positive significant heterosis among the genotypes for harvest duration, one cross for the number of seeds per pod, and one cross for the hundred seed weight, suggesting limited impact on these traits. Three crosses demonstrated considerable positive heterosis for average pod dry weight. Three crosses exhibited strong positive heterosis for total sugar. Eleven cross combinations revealed significant positive heterosis for total polyphenol content. Thirteen crosses showed positive significant heterosis for total protein and total nitrogen. For mucilage content, 20 F_1 hybrids showed positive significant heterosis.

Combining ability effects

General combining ability (GCA)

The average performance of a genotype in a series of hybrid combinations is referred to as GCA. These effects are observed where different parental genotypes are evaluated for various traits related to plant growth, yield, and biochemical composition. GCA is a measure of how well a genotype contributes to the overall performance of certain traits. Positive significant GCA effects indicate that a particular genotype positively influences the expression of specific characteristics. Data pertaining to GCA is depicted in Table 5 and Supplementary Fig. 1. UHFO-9 had positive significant GCA effects for first flowering node. For plant height, UHFO-10 followed by UHFO-14 and UHFO-9 had positive significant GCA effects. UHFO-8, UHFO-6 and UHFO-7 observed positive significant GCA effects. Pusa Bhindi-5 and Arka Anamika showed positive significant GCA effects for primary number of branches per plant. For number of pods per plant, UHFO-6 and UHFO-9 had significant positive GCA effects. UHFO-3 had significant positive GCA effects for average pod weight, UHFO-6 and UHFO-9 for pod yield per plant, Pusa Bhindi-5 for days to first picking, UHFO-8 for hundred seed weight and UHFO-9 for average pod dry weight. Various genotypes showed positive significant GCA effects for different biochemical components (total sugar, total polyphenol, total protein, total nitrogen, mucilage content), indicating their potential impact on these traits. Days to 50 per cent flowering, pod length, pod diameter, harvest duration and number of seeds per pod had non-significant GCA effects.

Table 5
Estimates of general combining ability (GCA) for 20 traits in line × tester mating design of okra

Hybrids Traits	UHFO-2	UHFO-3	UHFO-4	UHFO-5	UHFO-6	UHFO-7	UHFO-8	UHFO-9	UHFO-10	UHFO-14	Arka Anamika	Pusa Bhindi-5	Hisar Unnat
DF	1.81	-2.15	3.51	-2.04	1.44	-2.15	-1.26	0.03	0.96	-0.15	-1.52	-0.66	2.18
FF	-0.26	0.07	-0.70	-0.15	-0.22	0.30	0.63	**0.33***	1.04	-1.04	-0.34	-0.03	0.37
PH	-18.76	-0.36	**2.54***	-18.33	-22.52	3.99	-32.87	**21.19***	**42.26***	**22.85***	**-4.41***	-0.50	4.92
IL	1.41	-1.07	**-0.43***	-2.37	**-1.86***	**-1.62***	**-3.71***	3.75	3.04	**2.86***	-0.12	-0.42	0.54
BP	**-0.03***	0.33	0.17	-0.07	-0.38	0.27	0.29	-0.05	-0.51	**-0.04***	**0.09***	**0.10***	-0.18
PL	-0.88	0.80	0.53	-0.44	2.59	0.26	-0.44	-0.27	-1.01	-1.14	-0.02	0.33	-0.31
PD	0.00	0.00	-0.03	-0.17	0.10	0.07	0.03	0.03	-0.03	0.00	0.01	0.02	-0.02
PP	3.06	**-3.39***	**-1.21***	-1.54	**4.58***	-1.60	-1.30	**2.52***	-2.15	1.03	0.65	0.49	-1.14
PW	-0.31	**0.17***	-0.64	-1.99	3.17	-0.08	**-0.45***	**-0.79***	-0.70	1.62	0.34	-0.12	-0.22
PYP	25.10	**-25.79***	**-24.45***	**-50.14***	**123.47***	-15.24	-19.93	**7.49***	-31.39	10.89	13.18	3.42	-16.60
FP	-0.33	1.78	3.22	2.55	-6.00	-3.78	2.78	-3.11	**3.78***	-0.89	-0.7	**-0.03***	**0.73***
HD	-1.47	0.02	-4.29	**-10.25***	5.27	1.12	-0.10	5.50	-0.84	5.02	0.01	2.75	-2.75
SP	-1.62	4.62	-2.79	-8.51	4.58	1.01	0.89	-1.5	-1.58	4.89	-1.01	0.93	0.08
SW	-0.61	-0.05	0.29	-0.55	0.64	0.42	**0.19***	0.29	-0.29	**-0.35***	-0.09	0.18	-0.09
DW	**-0.05***	0.21	0.11	-0.16	0.15	**-0.05***	**-0.12***	**0.07***	-0.01	**-0.15***	-0.03	0.04	-0.01
TS	**-0.50***	**0.35***	**-0.40***	**1.87***	**0.28***	0.00	**0.34***	**-0.07***	**-0.75***	**-1.11***	**0.12***	-0.21	0.09
TPP	**-0.06***	-0.02	**0.08***	**-0.17***	**-0.09***	**-0.06***	**0.15***	**-0.12***	**0.49***	**-0.19***	**0.11***	-0.03	-0.08
TP	**6.09***	**-2.00***	**0.57***	**-1.49***	**5.33***	**-5.58***	**-5.37***	**-1.49***	**4.15***	-0.21	-1.28	**1.07***	0.21
TN	**0.97***	**-0.32***	**0.09***	**-0.24***	**0.85***	**-0.90***	**-0.86***	**-0.24***	**0.69***	-0.04	-0.21	**0.18***	0.03
MC	-0.09	**0.07***	-0.06	**0.03***	0.07	-0.01	**0.06***	**-0.06***	**0.04***	-0.05	0.01	**-0.01***	**0.00***

Where, DF: days to 50 per cent flowering, FF: first flowering node, PH: plant height, IL: inter-nodal distance, BP: number of primary branches per plant, PL: pod length, PD: pod diameter, PP: number of pods per plant, PW: average pod weight, PYP: pod yield per plant, FP: days to first picking, HD: harvest duration, SP: number of seeds per pod, SW: hundred seed weight, DW: average dry weight of pod. TS: total sugars, TPP: total polyphenol, TP: total protein, TN: total nitrogen and MC: mucilage content

Specific combining ability (SCA)

SCA is the parent's relative performance in a certain cross. These effects are observed where various crosses between different genotypes are evaluated for a range of traits related to plant development, yield, and biochemical composition. SCA measures the relative performance of specific crosses, and positive or negative significant SCA effects indicate the impact of the specific combination on the traits of interest. Data pertaining to SCA is depicted in Table 6–7 and Supplementary Fig. 2. For days to 50 per cent flowering, crosses UHFO-6 × Hisar Unnat and UHFO-4 × Hisar Unnat displayed significant negative SCA effects. UHFO-9 × Hisar Unnat had significant negative SCA effects for first flowering node. For plant height, significant positive SCA effects were observed for UHFO-5 × Hisar Unnat and UHFO-7 × Hisar Unnat. Cross UHFO-2 × Arka Anamika displayed negative significant SCA effects for inter-nodal length. For pod length, significant positive SCA effects were observed for UHFO-9 × Pusa Bhindi-5, UHFO-6 × Hisar Unnat and UHFO-14. × Arka Anamika. UHFO-2 × Pusa Bhindi-5 was considered best for pod diameter. For average pod weight, positive significant SCA effects were observed for UHFO-2 × Pusa Bhindi-5, UHFO-10 × Hisar Unnat and UHFO-2 × Arka Anamika. UHFO-5 × Hisar Unnat, UHFO-6 × Pusa Bhindi-5 and UHFO-9 × Hisar Unnat expressed significant positive effects for number of pods per plant. Positive significant SCA effects for pod yield per plant were observed for UHFO-2 × Pusa Bhindi-5, UHFO-10 × Hisar Unnat, UHF-2 × Arka Anamika and UHF-5 × Arka Anamika. UHF-2 × Arka Anamika was considered best for days to first picking. Crosses UHFO-7 × Hisar Unnat, UHFO-4 × Pusa Bhindi-5 and UHFO-9 × Pusa Bhindi-5 showed positive significant SCA effects for harvest duration. For number of seeds per pod, SCA effects were positively significant for UHFO-8 × Hisar Unnat, UHFO-6 × Pusa Bhindi-5 and UHFO-3 × Pusa Bhindi-5. For hundred seed weight, UHFO-8 × Hisar Unnat, UHFO-9 × Pusa Bhindi-5 and UHFO-14 × Hisar Unnat displayed positive significant SCA effects. UHFO-6 × Hisar Unnat, UHFO-9 × Pusa Bhindi-5 and UHFO-8 × Pusa Bhindi-5 had Positive significant SCA effects for average pod dry weight. Various genotypes showed positive significant SCA effects for different biochemical components (total sugar, total polyphenol, total protein, total nitrogen, mucilage content), indicating their potential impact on these traits. Number of primary branches per plant had non-significant SCA effects.

Table 6
Estimates of specific combining ability (SCA) for 20 traits in line × tester mating design of okra

Hybrids \ Traits	DF	FF	PH	IL	BP	PL	PD	PP	PW	PYP
UHFO-2 × AA	1.22	-0.36	**-0.04***	**-0.87***	0.37	1.26	-0.14	-0.53	1.04	**17.42***
UHFO-2 × PB	2.37	-0.45	-0.27	0.67	-0.82	0.38	**0.15***	1.13	**1.28***	**38.29***
UHFO-2 × HU	-3.59	**0.82***	0.30	0.20	0.44	-1.65	-0.01	-0.60	-2.32	-55.71
UHFO-3 × AA	0.19	-0.70	0.34	0.87	0.10	-0.31	0.06	1.95	0.35	23.73
UHFO-3 × PB	-2.34	0.99	0.43	-0.72	-0.01	-0.26	-0.05	-1.43	0.41	-9.01
UHFO-3 × HU	2.15	-0.3	-0.77	-0.16	-0.09	**0.57***	-0.01	-0.52	-0.75	-14.72
UHFO-4 × AA	-2.37	0.08	2.36	1.36	-0.04	1.25	0.09	-2.50	0.32	-13.93
UHFO-4 × PB	2.66	0.55	-0.33	-0.11	0.13	-1.40	-0.21	3.98	-1.25	6.32
UHFO-4 × HU	**-0.29***	-0.63	**-2.02***	-1.25	-0.09	**0.14***	0.12	**-1.49***	0.94	7.61
UHFO-5 × AA	3.30	0.53	-1.11	-0.37	0.04	-0.78	0.13	2.55	-0.15	**15.06***
UHFO-5 × PB	0.66	-1.01	**-0.74***	**0.27***	0.20	-0.43	-0.08	-2.92	1.02	-6.51
UHFO-5 × HU	-3.96	0.48	**1.85***	0.10	-0.23	1.21	-0.04	**0.36***	-0.87	**-8.55***
UHFO-6 × AA	-1.07	-0.4	-1.31	0.01	-0.18	-1.11	-0.04	-0.03	**-0.33***	-4.36
UHFO-6 × PB	**3.40***	-0.71	1.71	-0.14	0.18	**-0.06***	-0.05	**1.41***	-0.39	7.60
UHFO-6 × HU	**-2.33***	1.11	-0.41	0.13	0.00	**1.17***	0.09	-1.37	0.72	-3.24
UHFO-7 × AA	-0.82	-0.03	-0.73	**0.44***	-0.30	-1.88	-0.11	1.28	-0.53	1.02
UHFO-7 × PB	-2.23	0.88	-0.84	-0.11	0.15	2.87	0.08	-2.96	0.60	-17.62
UHFO-7 × HU	**3.04***	-0.85	**1.57***	-0.33	0.16	-0.99	0.02	1.68	-0.06	16.60
UHFO-8 × AA	-4.70	-0.70	-1.15	-0.24	-0.13	0.72	0.13	0.32	-0.84	-13.61
UHFO-8 × PB	5.11	**0.44***	0.83	0.63	0.17	-1.42	-0.09	2.87	-0.05	24.43
UHFO-8 × HU	-0.40	**0.26***	0.33	-0.39	-0.04	**0.71***	-0.04	-3.19	0.89	-10.82
UHFO-9 × AA	4.00	0.71	-1.49	-0.80	0.19	-0.45	-0.17	-0.50	**0.00***	-3.79
UHFO-9 × PB	-4.19	-0.27	-0.24	1.23	-0.15	**1.90***	0.22	-0.84	-0.11	-12.21
UHFO-9 × HU	0.19	**-0.44***	1.74	-0.43	-0.04	-1.46	-0.04	**1.34***	0.11	16.01
UHFO-10 × AA	3.07	0.45	**-0.11***	1.22	-0.07	0.49	0.09	-1.53	-0.15	-16.87
UHFO-10 × PB	-4.45	-0.64	1.79	-2.75	-0.18	-1.36	-0.11	-0.88	-0.72	-21.94
UHFO-10 × HU	1.37	0.19	-1.68	1.53	0.25	0.87	0.02	2.41	0.87	**38.81***
UHFO-14 × AA	-2.81	0.42	3.25	-1.63	0.01	**0.82***	-0.04	-1.01	**0.30***	-4.67
UHFO-14 × PB	-1.00	0.21	-2.34	1.03	0.34	-0.23	0.15	-0.36	-0.77	-9.33
UHFO-14 × HU	3.82	-0.63	**-0.91***	**0.59***	-0.35	-0.59	-0.11	1.37	**0.48***	14.00

*Significant at 5% level of significance.

Where, AA: Arka Anamika, PB: Pusa Bhindi-5, HU: Hisar Unnat, DF: days to 50 per cent flowering, FF: first flowering node, PH: plant height, IL: inter-nodal distance, BP: number of primary branches per plant, PL: pod length, PD: pod diameter, PP: number of pods per plant, PW: average pod weight and PYP: pod yield per plant.

Table 7
Estimates of specific combining ability (SCA) for 20 traits in line × tester mating design of okra

Hybrids \ Traits	FP	HD	SP	SW	DW	TS	TPP	TP	TN	MC
UHFO-2 × AA	3.03	-9.20	-0.46	-0.11	-0.09	**0.22***	**0.13***	**-3.46**	**-0.55***	0.02
UHFO-2 × PB	0.03	3.73	-3.47	**0.14***	**0.12***	**0.77***	**0.03***	**0.71***	**0.11***	**0.14***
UHFO-2 × HU	-3.07	5.47	3.93	-0.04	-0.04	-0.99	-0.15	**2.75***	**0.45***	-0.17
UHFO-3 × AA	-1.08	2.53	-3.00	-0.02	**0.24***	**-0.84**	-0.14	**-1.72***	**-0.27***	-0.07
UHFO-3 × PB	0.59	-1.50	**2.08***	**0.96***	-0.01	**0.08***	**0.10***	**3.56***	**0.56***	**0.04***
UHFO-3 × HU	0.49	**-1.02***	**0.92***	-0.94	-0.23	**0.76***	**0.04***	-1.84	-0.29	**0.04***
UHFO-4 × AA	-1.52	-4.96	0.69	**1.62***	0.08	**1.20***	**0.43***	-2.26	-0.36	**-0.03***
UHFO-4 × PB	1.48	**2.34***	0.42	-1.06	-0.18	-0.30	-0.20	**-4.58***	**-0.74***	-0.09
UHFO-4 × HU	0.04	2.62	-1.11	-0.56	**0.10***	-0.90	-0.23	**6.84***	**1.10***	**0.12***
UHFO-5 × AA	-0.19	4.48	3.00	-0.11	0.11	**-0.39***	**-0.06***	-0.27	-0.04	**0.04***
UHFO-5 × PB	-2.85	-2.61	-3.02	0.05	**0.07***	**-0.30***	**0.08***	**8.57***	**1.37***	-0.05
UHFO-5 × HU	3.05	-1.87	0.02	0.06	-0.17	**0.69***	**-0.02**	-8.30	-1.32	0.02
UHFO-6 × AA	1.70	-3.44	-0.54	-0.61	**0.09***	**0.38***	**-0.12**	**3.80***	**0.61***	**0.07***
UHFO-6 × PB	-0.97	1.85	**2.25***	**0.61***	-0.22	-0.07	**0.22***	**-8.87***	**-1.42***	**0.05***
UHFO-6 × HU	-0.73	1.58	-1.71	0.00	**0.14***	**-0.32***	**-0.10***	**5.07***	**0.82***	-0.11
UHFO-7 × AA	1.81	-1.96	0.03	**0.64***	-0.17	**-1.12***	**-0.38***	**4.77***	**0.77***	0.08
UHFO-7 × PB	0.48	0.30	**0.45***	-0.62	0.11	**-0.09***	**0.07***	-2.92	-0.47	-0.12
UHFO-7 × HU	-2.29	**1.66***	-0.48	**-0.02***	**0.06***	**1.22***	**0.31***	-1.85	-0.29	**0.04***
UHFO-8 × AA	1.59	4.56	-3.99	0.11	-0.16	**0.10**	**-0.23***	**7.63***	**1.22***	**0.00***
UHFO-8 × PB	1.26	-6.21	-0.52	-0.62	**0.11***	-1.08	**-0.31***	-2.35	**-0.38***	-0.08
UHFO-8 × HU	-2.84	1.65	**4.51***	**0.51***	**0.04***	**0.99***	**0.53***	**-5.28***	-0.84	**0.08***
UHFO-9 × AA	-2.52	4.50	0.82	-0.46	**0.01***	**0.94***	**-0.24***	**1.68***	**0.27***	-0.03
UHFO-9 × PB	-1.19	**1.96***	0.94	**0.50***	**0.12***	**0.45***	**0.12***	**0.52***	**0.08***	**0.04***
UHFO-9 × HU	**3.71***	-6.46	-1.76	-0.04	-0.12	**-1.40***	**0.11***	**-2.20***	**-0.35***	-0.01
UHFO-10 × AA	**-0.41***	1.68	2.52	-0.85	0.00	-0.41	**0.53***	**-8.33***	**-1.36***	**0.01***
UHFO-10 × PB	1.59	-0.61	0.32	0.22	**-0.09***	**0.50***	**0.04***	**5.73***	**0.97***	0.04
UHFO-10 × HU	-1.18	**-1.07***	-2.84	0.63	0.10	**-0.09***	**-0.56***	**2.60***	**0.39***	**-0.05***
UHFO-14 × AA	-2.41	1.82	**0.93***	-0.22	-0.10	-0.08	**0.08***	**-1.84***	**-0.29***	-0.08
UHFO-14 × PB	-0.41	0.75	**0.54***	-0.19	-0.03	0.05	**-0.15***	-0.38	-0.07	0.03
UHFO-14 × HU	2.82	-2.57	**-1.47***	**0.41***	0.13	**0.03***	**0.07***	**2.21***	**0.36***	0.05

*Significant at 5% level of significance.

Where, AA: Arka Anamika, PB: Pusa Bhindi-5, HU: Hisar Unnat, FP: days to first picking, HD: harvest duration, SP: number of seeds per pod, SW: hundred seed weight, DW: average dry weight of pod. TS: total sugars, TPP: total polyphenol, TP: total protein, TN: total nitrogen and MC: mucilage content.

Discussion

Three were discovered by Bhatt et al. (2016)[8], seven by Koli et al. (2020)[9], and eleven crosses demonstrating positive and significant standard/economic heterosis for fruit yield per plant were discovered by Karadi et al. (2021)[10]. Six crosses for total sugar and four for total phenols were identified by Das et al. (2022)[11] to exhibit positive and significant standard/economic heterosis. Fourteen were discovered by Bhatt et al. (2016)[8], twelve by Kumar et al. (2021)[12], and seven crosses demonstrating positive and significant heterobeltiosis for fruit yield per plant were discovered by Karadi et al. (2021)[10]. Sixteen crosses for total sugar and three for total phenols were identified by Das et al. (2022)[11] to exhibit positive and significant heterobeltiosis.

The existence of less good general combiners, especially for yield and its contributing traits, emphasised the identification of appropriate genotypes for further breeding programme to develop superior hybrids in subsequent generations. Tiwari et al. (2016)[13] discovered VRO-6 to be a good general combiner for yield per plant, as well as other traits such as first flowering node, days to first flowering, days to 50 per cent flowering, days to first picking, internodal length, days to last picking, number of fruits per plant, and number of branches per plant. Patel et al. (2021)[14] discovered just one parent as a good combiner for yield per plant, but Narkhede et al. (2021)[15] discovered two. Das et al. (2020)[16] identified three lines and one tester as good combiners for total sugar and two lines and one tester for total phenols. Tiwari et al. (2016)[13] identified three cross combinations as good specific combiners for yield per plant, number of fruits per plant, ascorbic acid, average fruit weight, days to first flowering, and fruit diameter. Narkhede et al. (2021)[15] discovered 19, Patel et al. (2021)[14] discovered three, and Subakar et al. (2022)[17] discovered three crosses as good specific combiners for yield per plant. Das et al. (2020)[16] discovered four specific combiners for total sugars and 10 for total phenols.

The chosen okra genotypes exhibited substantial variability in all of the traits evaluated in this study. The main goal of this study was to determine the amount of combining ability effects in okra in order to produce novel F_1 hybrids with increased pod yield. In this study, heterosis analysis and combining ability analysis effectively identified good combiners which can be used in further breeding programmes and may serve as guideposts in establishing an integrated strategy for okra enhancement. Genotypes UHFO-6 and UHFO-9 were revealed to be good general combiners among parents whereas crosses UHFO-2 × Pusa Bhindi-5, UHFO-10 × Hisar Unnat and UHFO-2 × Arka Anamika displayed statistically significant SCA effects and standard heterosis for almost all of the traits. As a consequence, such crosses might be utilized for heterosis breeding, and the parents could be exploited in future breeding efforts to develop desired okra varieties/hybrids.

Methods

Location

The present investigation was carried out at Vegetable Research Farm and Quality Analysis Laboratory, Department of Vegetable Science, College of Horticulture, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh, India (77˚ 11' 30" E and 30˚ 52' 30" N) during years 2021 and 2022, respectively.

Planting material

The experimental material included 13 genotypes (ten lines and three testers). The Department of Vegetable Science, Dr. YSP UHF, Solan provided the 10 parental lines, and testers were received from CCS HAU (Hisar, Haryana), ICAR-IARI (New Delhi), and ICAR-IIHR (Bengaluru, Karnataka). In the spring-summer season of 2020, the parents were sowed at 60 cm × 45 cm spacing to develop 30 crosses (Supplementary Table 2). The seeds of thirteen parental genotypes and 30 F_1 hybrids were taken from the first season and seeded in Randomised Complete Block Design with three replications at a spacing of 60 cm × 30 cm with standard check (commercial variety) Punjab-8 (PAU, Ludhiana, Punjab) during summer 2022 for estimation of standard heterosis. The standard cultural practices recommended for raising the healthy crop of okra as per the “Package of Practices for Vegetable Crops” by Dr Y.S. Parmar University of Horticulture and Forestry, Nauni, Solan, HP were followed. Data for 14 morphological and 6 biochemical traits were obtained [DF: Days to 50 per cent flowering; FF: First flowering node; PH: Plant height (cm); IL: Inter-nodal length (cm); BP: Number of primary branches per plant; PL: Pod length (cm); PD: Pod diameter (cm); PP: Number of pods per plant; PW: Average pod weight (g); PYP: Pod yield per plant (g); FP: Days to first picking; HD: Harvest Duration; SP: Number of seeds per pod; SW: Hundred seed weight (g); DW: Average dry weight of pod (g); TS: Total sugar (%); TPP: Total polyphenol (%); TP: Total protein (%); TN: Total nitrogen (%); MC: Mucilage content (g)]. For data collection, ten plants per genotype per replication were chosen at random and tagged. Except for pod yield, data were collected from chosen plants. Pod dry weight was calculated by dividing weight of dried pods with total number of pods used for drying using weighing balance. Total sugars were estimated using the procedure given by Dubois *et al.* (1956)[18]. Total polyphenol was determined by a spectrophotometric method using Folin-Ciocalteu reagent with Gallic acid as the standard. Total protein content was estimated as suggested by Lowry *et al.* (1951)[19]. The nitrogen content in pod was calculated by dividing protein content of the green pod with the factor of 6.25. To determine mucilage concentration, the sample was cleaned and dried in an oven. The powdered substance was boiled in water, and the concentrated solution was filtered through muslin fabric. Mucilage was separated using acetone and dried in a hot air oven.

$$\text{Mucilage content (g)} = \frac{\text{Weight of dried mucilage (g)}}{\text{Weight of powdered pod taken (g)}}$$

Statistical analysis

ANOVA for Randomised Complete Block Design was performed according to Panse and Sukhatme (1985)[20]. Each trait's mean value was computed by dividing the total value by the number of observations. The percentage increase or reduction in mean F_1 performance over the heterobeltiosis as well as the standard check was used to compute heterosis. Heterosis was calculated as followed by Fonseca and Patterson (1968)[21] using Microsoft Excel 365 and the T-test was used to determine significance using standard error (Wynne et al. 1970)[22]. For Line × Tester mating design, Kempthorne (1957)[23] provided thorough instructions for doing the combining ability analysis and was calculated on Microsoft Excel 365 and OP-STAT (Sheoran et al. 1998)[24].

Declarations

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh, India, for their assistance with the study and for supplying the essential materials.

AUTHOR CONTRIBUTIONS

A.D.R.: Data curation, Formal analysis, original draft preparation, supervision. A.V.: Conceptualization, data curation, formal analysis, investigation, methodology, original draft preparation, supervision. R.K.: Data curation, investigation, methodology, original draft preparation, supervision. R.K.D.: Formal analysis, investigation, methodology, supervision. R.S.: Investigation, supervision. H.R.S.: Investigation, methodology, supervision.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article and in its supplementary materials. Raw data is available on request to corresponding authors.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Datta, P.C. & Naug, A. A few strains of *Abelmoschus esculentus* (L.) Moench. Their karyological study in relation to phylogeny and organ development. Beiträge zur Biologie der Pflanzen 45, 113–126 (1968).
2. Agricultural Statistics at a Glance (2022). Economics & Statistics Division, Department of Agriculture & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India. Available at < https://desagri.gov.in/wp-content/uploads/2023/05/Agricultural-Statistics-at-a-Glance-2022.pdf>
3. National Horticulture Board (2022) First Advance Estimate of 2021-22. Area and Production of Vegetable Crops. Ministry of Agriculture & Farmers Welfare. Government of India. Available at < https://static.pib.gov.in/WriteReadData/specificdocs/documents/2022/mar/doc202232832101.pdf>
4. Thamburaj, S. & Singh,N. Textbook of Vegetable, Tubercrops and Spices. Indian Council of Agricultural Research, New Delhi, India. 490p (2018).
5. Ranga, A.D., Vikram, A., Kumar, R., Dogra, R.K., Sharma, R., & Bairwa M.K. Genetic assessment and potence ratio of various traits of okra (*Abelmoschus esculentus*) in mid hills of Himachal Pradesh, Indian Journal of Agricultural Sciences. 94, (1) 26–32 (2024). 10.56093/ijas.v94i1.139435
6. Labroo, M.R., Studer, A.J., & Rutkoski, J.E. Heterosis and Hybrid Crop Breeding: A Multidisciplinary Review, *Frontiers in Genetics*. 12, (2021). *10.3389/fgene.2021.643761*
7. Yadav, K., Dhankhar, S.K., Singh, D., Singh, U., Amit & Yogita. Exploitation of combining ability and heterosis potential for improvement in okra (*Abelmoschus esculentus*) genotypes. *Indian Journal of Agricultural Science*s 93, 127–132 (2023). 10.56093/ijas.v93i2.132161
8. Bhatt, J.P., Patel, N.A., Acharya, R.R. & Kathiria, K.B. Heterosis for yield and its related traits in okra (*Abelmoschus esculentus* L. Moench). Electronic Journal of Plant Breeding. 7, 189–196 (2016). 10.5958/0975-928X.2016.00026.0
9. Koli, H.K., Patel, A.I., Vshai, J.M. & Chaudhari, B.N. Study of heterosis for fruit yield and its component traits in okra [*Abelmoschus esculentus* (L.) Moench]. International Journal of Current Microbiology and Applied Sciences. 9, 1930–1937 (2020). 10.20546/ijcmas.2020.909.242
10. Karadi, S.M. & Hanchinamani, C.N. Estimation of heterosis in okra [*Abelmoschus esculentus* (L.) Moench] for fruit yield and its components through line × tester mating design. Bangladesh Journal of Botany. 50, 531–540 (2021). 10.3329/bjb.v50i3.55832
11. Das, A., Yadav, R.K., Bhardwaj, R., Choudhary, H. & Khade, Y.P. Study of heterotic potential for important antioxidant and nutritional traits in okra (*Abelmoschus esculentus*). Indian Journal of Agricultural Sciences. 92, 986–990 (2022). 10.56093/ijas.v92i8.110389
12. Kumar, A., Gaurav, S.S., Shiri, T. Heterosis and inbreeding depression in okra (*Abelmoschus esculentus* (L.) Moench). The Pharma Innovation Journal. 10, 793–798 (2021).

13. Tiwari, J.N., Kumar, S. & Ahlawat, T.R. Combining ability studies for various horticultural traits in okra [*Abelmoschus esculentus* (L.) Moench] under South-Gujarat conditions. Journal of Farm Sciences. 29, 53–56 (2016).

14. Patel, B.M., Vachhani, J.H., Godhani, P.P., & Sapovadiya, M.H. Combining ability for fruit yield and its components in okra [*Abelmoschus esculentus* (L.) Moench]. Journal of Pharmacognosy and Phytochemistry. 10, 247–251 (2021).

15. Narkhede, G.W., Thakur, N.R. & Ingle, K.P. Studies on combining ability for yield and contributing traits in okra [*Abelmoschus esculentus* (L.) Moench]. Electronic Journal of Plant Breeding. 12, 403–412 (2021).

16. Das, A., Yadav, R.K., Bhardwaj, R., Choudhary, H., Talukdar, A., Khade, Y.P., & Chandel R. Combining ability and gene action studies to select okra [*Abelmoschus esculentus* (L.) Moench] inbred for carbohydrate, vitamins and antioxidant traits. Indian Journal of Agricultural Sciences. 90, 2006–2013 (2020). 10.56093/ijas.v90i10.107982

17. Subakar, I.J.J., Reeth, J.G., Greetty, W. S., Vennila & Anbuselvam, Y. Study of line x tester analysis for combining ability in bhendi [*Abelmoschus esculentus* (L.) Moench]. Crop Research. 57, 38–43 (2022). 10.31830/2454-1761.2022.006

18. Dubois, M.K., Gills, A., Hamilton, J.K., Rebarg, P.R., Smith F. Colorimeteric method for determination of sugars and related substances. Ann. Chem. 28, 350–356 (1956). 10.1038/168167a0

19. Lowry, H.O., Rosebrough, N.J., Farr, A.L. & Randall, R.J. Protein measurement with the Folin phenol reagent. Journal of Biological Chemistry. 193 (1951) 265–75. 10.1016/S0021-9258(19)52451-6

20. Panse, V.G. & Sukhatme, P.V. Statistical Methods for Agricultural Workers, Indian Council of Agricultural Research Publication, New Delhi. 359p (1985).

21. Fonseca, S. & Patterson, F. Hybrid vigour in seven parent diallel crosses in common winter wheat (*Triticum aestivum* L.). Crop Science. 8, 85–95 (1968).

22. Wynne, J.C., Emery, D.A. & Rice, P.W. Combining ability estimation in *Arachis hypogaea* L. II. Field performance of F_1 hybrids. Crop Science. 10, 713–715 (1970). 10.2135/cropsci1970.0011183X001000060036x

23. Kempthorne, O. An introduction to genetical statistics. John Wiley and Sons, New York, 545p (1967).

24. Sheoran, O.P., Tonk, D.S., Kaushik, L.S., Hasija, R.C. & Pannu, R.S. Statistical Software Package for Agricultural Research Workers. Recent Advances in information theory, Statistics & Computer Applications by D.S. Hooda & R.C. Hasija Department of Mathematics Statistics, CCS HAU, Hisar. 139–143 (1998). Available at < http://14.139.232.166/opstat/>

Figures

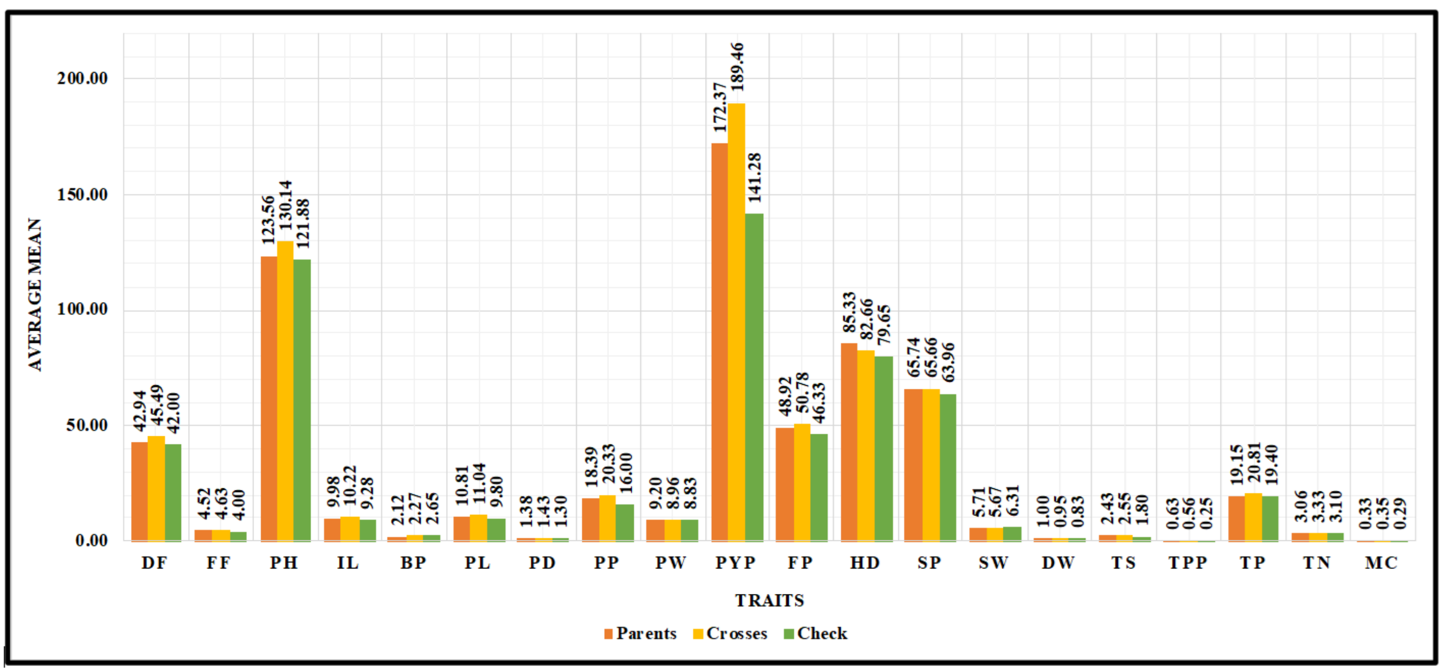

Figure 1

Average mean performance of parents, crosses and check

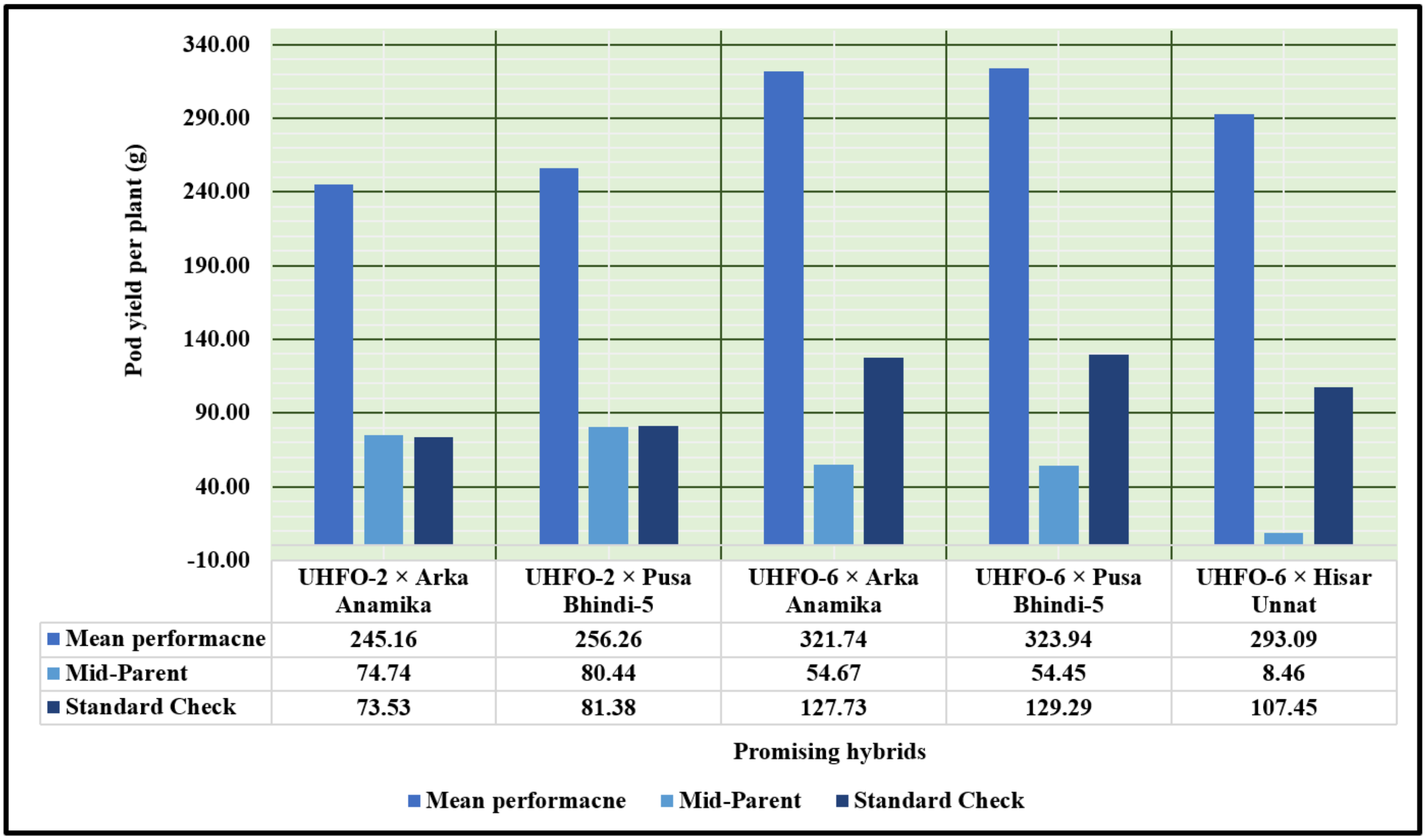

Figure 2

Per cent better parent and standard check heterosis in promising hybrids for pod yield per plant in okra

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryFiles.docx