



RESEARCH ARTICLE

Genetic analysis of yield and yield components through combining ability and heterosis studies in okra [*Abelmoschus esculentus* (L.) Moench]

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Abstract

The present study was conducted to evaluate combining ability, gene action and heterosis for important quantitative traits. The experimental material comprised 28 F₁ hybrids developed from eight diverse parental genotypes along with one standard check, Pusa Bhindi-5. The investigation was undertaken during the academic year 2024–25 at Eternal University, Baru Sahib (Himachal Pradesh, India). The analysis revealed considerable genetic variability among parents and hybrids, indicating a broad genetic base for effective selection and hybrid development. Hybrids such as Arka Anamika × Prabhani Kranti, Arka Anamika × Kashi Pragati, Pusa Bhindi × Kashi Lalima and Punjab-8 × Arka Anamika performed well for earliness, yield and yield-attributing traits. Heterosis analysis showed significant positive and negative effects, with desirable negative heterosis for earliness, yield and yield-contributing traits. Combining ability analysis identified Arka Anamika, Prabhani Kranti and Kashi Pragati as good general combiners for several traits, while several crosses exhibited high specific combining ability. The predominance of non-additive gene action for most traits suggests the potential of hybrid breeding for improving yield and traits in okra.

Keywords: combining ability; diallel analysis; earliness; gene action; heterosis; yield

Introduction

Okra (*Abelmoschus esculentus* L.), also known as lady's finger, is one of the most important nutrient-rich vegetable crops cultivated in tropical and hot temperate regions of the world because of its edible fibrous pods (1). As a summer vegetable grown mostly in tropical and subtropical areas of the world, it has substantial commercial value. Day temperatures ranging from 25–40 °C, along with night temperatures above 22 °C, are considered optimal for growth; temperatures below 29 °C significantly restrict seed germination (2). The crop has a relatively short growing period, requiring approximately 90–120 days to complete its life cycle under favourable growing conditions. Okra is grown in more tropical regions of the world due to its high nutritional value and rapid growth in hot conditions. Okra can be grown in a variety of soil types. It can be cultivated on a wide range of soils; however, well-drained sandy loam, loam and clay loam soils rich in organic matter are considered most suitable because they provide good aeration, drainage and moisture-holding capacity. The ideal pH range for soil is between 6.0 and 6.5 (3). Okra shows considerable variation in growth and yield traits depending on genotypes, environmental conditions and crop management. Under tropical and subtropical

conditions, plant height generally ranges from 80–180 cm, fruit length (8–15 cm), fruit diameter (11–14 mm), number of fruits per plant (15–35) and fruit yield per plant (130–300 g) (3).

Despite its adaptability to tropical and subtropical climates, okra production is significantly constrained by abiotic stresses such as drought, high temperature, salinity and waterlogging, which adversely affect plant growth, flowering, fruit set and yield. With increasing climate variability, the development of high-yielding cultivars has become an important objective of okra breeding programmes (4). Heterosis breeding has been widely recognised as an effective strategy for enhancing yield and other economically important traits in cross-pollinated vegetables. As the yield potential of many open-pollinated okra cultivars has reached a plateau, the development of superior hybrids has become increasingly important. The success of hybrid breeding largely depends on the selection of genetically diverse parents with good combining ability, as superior parental lines are more likely to transmit favourable alleles to their progeny (1). Therefore, combining ability analysis plays a crucial role in identifying suitable parents and cross combinations for developing high-yielding okra hybrids.

Although several studies have reported heterosis and combining ability in okra, information on the genetic potential of diverse parental lines and their hybrid combinations under the agroclimatic conditions of north western Himalayan regions remains limited. Identification of superior general and specific combiners is essential for developing high-yielding hybrids and formulating effective breeding strategies. Therefore, the present study was undertaken to estimate combining ability, heterosis and gene action for yield and yield-related traits using a half diallel mating design, to identify promising and hybrid combinations for future okra improvement programmes.

Materials and Methods

The field trial was conducted at the Dr. Khem Singh Gill Experimental Research Farm, Eternal University, Baru Sahib, Chhapang. This experiment was conducted at a location or research farm situated at 30°44'20" N latitude and 77°18'53" E longitude, 912 m above mean sea level. The crop was grown from March to August (2025) under subtropical conditions, with a mean temperature of 32.17 °C (max), 15.62 °C (min), 86.74 % relative humidity and annual rainfall of 1.88 mm during the experimental trial. The data are presented in Table 1.

The experimental material included eight different okra genotypes, i.e., Prabhani Kranti, Punjab Lalima, Kashi Pragati, Arka Anamika, Kashi Lalima, Punjab-8, Kashi Chaman and Pusa Bhindi, along with one standard check variety, i.e., Pusa Bhindi-5. A total of 28 F₁ hybrids were developed by crossing the eight parental lines in a half diallel mating design. The list of resulting hybrid combinations is provided in Table 2. The trial was laid out in a randomized block design with 3 replications and plants were spaced at 60 × 45 cm. Seeds were sown on 15th March, 2025. During the experimental trial, well-decomposed farmyard manure and urea were applied as nutrient sources. Standard agronomic practices were followed throughout the crop growing period. Recommended plant

protection measures were adopted to manage major insect pests, including jassids, aphids and whitefly and diseases as required. Mid parent heterosis (MP) refers to superiority of the F₁ hybrid over the mean performance of its parent. Better parent heterosis (Heterobeltiosis) refers to superiority of the F₁ hybrid over the better-performing parent and standard check heterosis (SC) refers to the superiority of the F₁ hybrid over the standard check variety. The estimation of heterosis was calculated as per the standard method (5). The relative heterosis, heterobeltiosis and economic heterosis were calculated with the following formula:

$$\text{Relative heterosis or average heterosis (Mid - parent heterosis)(\%)} = \frac{F_1 - MP}{MP} \times 100 \quad (\text{Eq. 1})$$

$$\text{Mid parent} = \frac{P_1 + P_2}{2} \quad (\text{Eqn. 2})$$

$$\text{Heterobeltiosis or Better parent heterosis (\%)} = \frac{F_1 - BP}{BP} \times 100 \quad (\text{Eq. 3})$$

$$\text{Economic heterosis or Standard heterosis (\%)} = \frac{F_1 - SC}{SC} \times 100 \quad (\text{Eq. 4})$$

Where,

MP = Mid parents; BP = Better parents; SC = Standard parents (6). Technique 2 model I was utilised to estimate the genetic component (σ^2_{gca} and σ^2_{sca}). Heterosis, GCA, SCA and the nature of gene action were analysed using Windostat version 9.2 Software.

Table 1. Meteorological data of the year 2025 (March–August)

	Temperature (°C)			Relative humidity (%) (Mean)	Rainfall (mm)
	Low	High	Mean		
March	18.46	26.29	18.46	56.16	0.09
April	15.62	31.86	23.77	48.20	0.12
May	18.04	32.17	25.13	65.16	2.49
June	20.84	31.80	26.35	73.70	1.66
July	21.82	30.22	26.05	85.26	1.88
August	21.45	29.37	25.44	86.74	1.81

Table 2. The list of hybrids developed from half diallel mating using 8 parents

1.	Punjab Lalima × Prabhani Kranti	15.	Punjab-8 × Kashi Lalima
2.	Kashi Pragati × Prabhani Kranti	16.	Kashi Chaman × Prabhani Kranti
3.	Kashi Pragati × Punjab Lalima	17.	Kashi Chaman × Punjab Lalima
4.	Arka Anamika × Prabhani Kranti	18.	Kashi Chaman × Kashi Pragati
5.	Arka Anamika × Punjab Lalima	19.	Kashi Chaman × Arka Anamika
6.	Arka Anamika × Kashi Pragati	20.	Kashi Chaman × Kashi Lalima
7.	Kashi Lalima × Prabhani Kranti	21.	Kashi Chaman × Punjab-8
8.	Kashi Lalima × Punjab Lalima	22.	Pusa Bhindi-5 × Prabhani Kranti
9.	Kashi Lalima × Kashi Pragati	23.	Pusa Bhindi-5 × Punjab Lalima
10.	Kashi Lalima × Arka Anamika	24.	Pusa Bhindi-5 × Kashi Pragati
11.	Punjab-8 × Prabhani Kranti	25.	Pusa Bhindi-5 × Arka Anamika
12.	Punjab-8 × Punjab Lalima	26.	Pusa Bhindi-5 × Kashi Lalima
13.	Punjab-8 × Kashi Pragati	27.	Pusa Bhindi-5 × Punjab-8
14.	Punjab-8 × Arka Anamika	28.	Pusa Bhindi-5 × Kashi Chaman

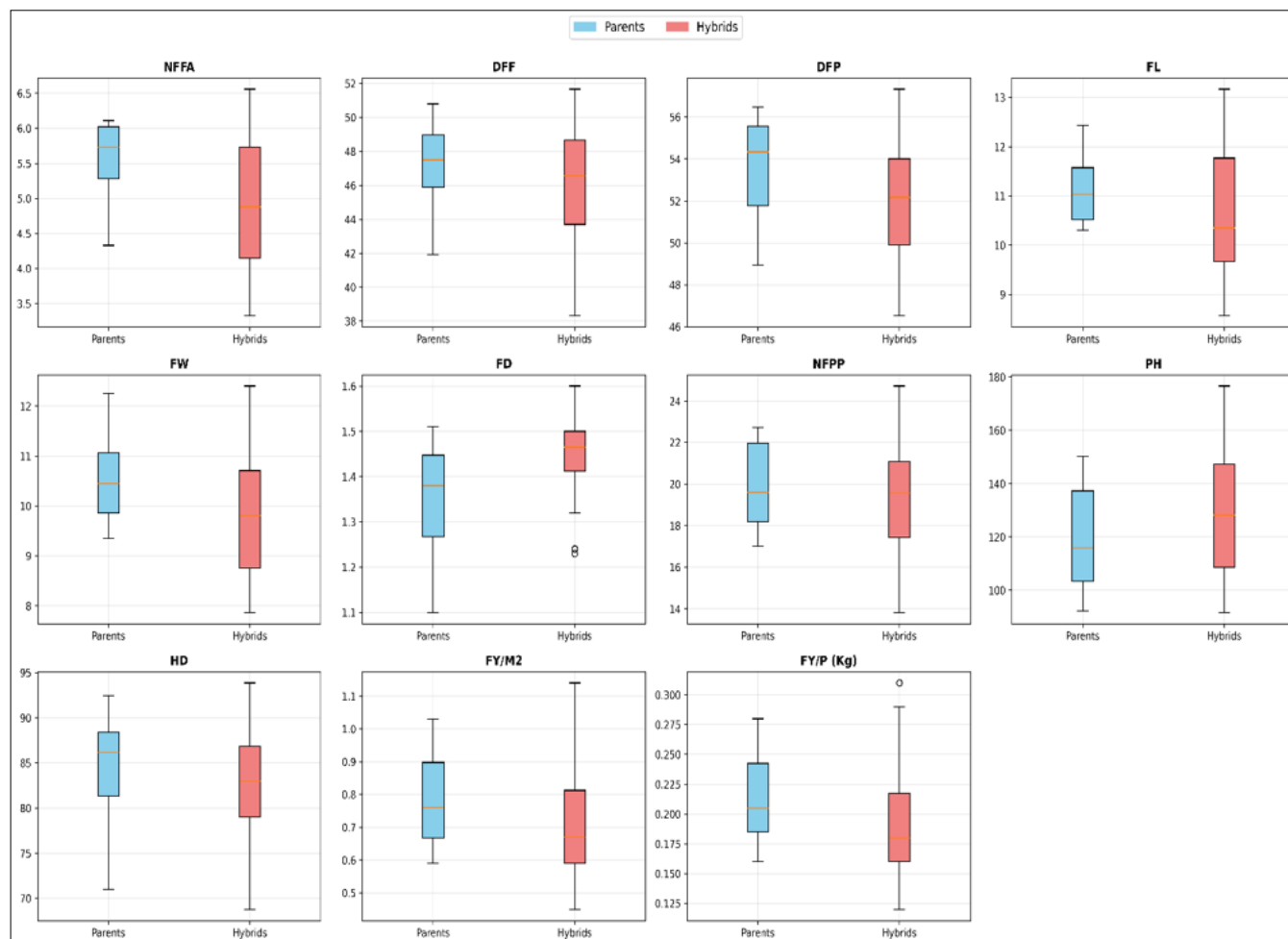


Fig. 1. Per se performance of parental vs hybrids.

NFFA = number of fruits at final harvest; DFF = days to first flowering; DFP = days to first picking; FL = fruit length (cm); FW = fruit width (cm); FD = fruit diameter (cm); NFPP = number of fruits per plant; PH = plant height (cm); HF = harvest frequency; FY/m² = fruit yield per square meter; FY/P = fruit yield per plant.

Results and Discussion

Significant genetic heterogeneity has been observed in all 11 quantitative traits between the eight parents and the 28 F₁ hybrids, indicating a wide genetic base for selection (Fig. 1). Out of all parents, Arka Anamika (4.33) was the earliest to record node bearing first flower whereas among hybrid combinations, Arka Anamika × Prabhani Kranti (3.33) showed significantly earlier appearance of the first flowering node and statistically at par with Arka Anamika × Kashi Pragati (3.35) and Punjab-8 × Arka Anamika (3.35). Among the parents, Pusa Bhindi-5 (41.93 days) exhibited the earliest flowering, followed by Punjab Lalima (43.40 days), whereas among the hybrid combinations, Pusa Bhindi-5 × Kashi Lalima (40.07 days). Out of all parental lines, Pusa Bhindi-5 (48.93 days) was the first to produce pods with the minimum number of days and was found to be statistically at par with Prabhani Kranti (48.96 days). Pusa Bhindi-5 × Kashi Lalima (46.53 days) was found to be the earliest hybrid to produce fruits and was statistically at par with Pusa Bhindi-5 × Arka Anamika (47.47 days). The early flowering observed may be due to the expression of favourable genes controlling earliness and heterotic effect that accelerate the transition from vegetative to reproductive growth. For fruit length, the maximum mean performance of the parent was noted in Arka Anamika (12.43 cm). While among hybrid combinations, Arka Anamika × Prabhani Kranti (13.17cm) recorded the maximum value, followed closely by Arka Anamika × Kashi Pragati (13.03 cm). With respect to fruit weight, maximum values were noted by Arka Anamika (12.35 g) and

Prabhani Kranti (11.36 g). In the hybrid combination, Arka Anamika × Prabhani Kranti (12.40 g) recorded the maximum fruit weight. The maximum mean performance for fruit diameter among parents was noted in Prabhani Kranti (1.51cm), followed by Arka Anamika (1.50). Parental line Arka Anamika (22.72) noted the highest number of fruits per plant, followed by Prabhani Kranti (22.52), whereas among hybrid combinations, Arka Anamika × Prabhani Kranti (24.72) was found to have maximum fruits/plant. These findings are in agreement with the findings reported by (5, 6). For plant height, the maximum value was noted in Arka Anamika (150.27 cm), subsequently followed by Prabhani Kranti (148.28 cm). Out of 21 hybrid combinations, Arka Anamika × Prabhani Kranti (176.64 cm) recorded maximum plant height, followed by Arka Anamika × Kashi Pragati (174.88cm). Parental line, Arka Anamika (92.42 days), had the longest harvest duration and was statistically at par with Prabhani Kranti (91.43), whereas in 21 hybrid combinations, Arka Anamika × Kashi Pragati (9.86 days) recorded the maximum number of days to harvest. Among the parents, Arka Anamika (1.03) recorded maximum fruit yield/m² followed by Prabhani Kranti (0.95). In hybrid combinations, Arka Anamika × Prabhani Kranti (1.14). The parental line (Arka Anamika- 0.28) produced maximum fruit yield/plant, followed by Prabhani Kranti (0.25). Out of all hybrid combinations, Arka Anamika × Prabhani Kranti (0.31) and Arka Anamika × Kashi Pragati (0.29) produced the highest fruit yield/plant. Superior performance of parents and hybrids with respect to plant height, number of fruits per plant, fruit length, fruit weight and yield may be

due to more favorable environmental conditions prevailing during the experimental trial, which promoted better growth and development. Environmental conditions are known to significantly influence the growth and development of okra. Similar findings have been reported in previous studies (6–9).

Estimation of heterosis (Mid parent, better parent and standard check)

The analysis of variance of heterosis for eleven quantitative traits has been given in Table 3. For the node at which the first flower appeared, 15, 17 and 8 hybrids out of 28 cross combinations exhibited significantly negative and desirable heterosis over mid parent, better parent and standard check, respectively. The higher negative heterosis over mid parent (-40.36) and better parent (-43.04) was noted in Kashi Chaman × Kashi Pragati and negative heterosis over standard check was obtained in Arka Anamika × Prabhani Kranti (-31.62). The presence of genes for the development of an early flowering node is revealed by the significant negative heterosis. The results are consistent with those of (10–11). For days to first flowering, negative heterosis for this trait is highly desirable in heterosis studies, as days to first flowering is a crucial indicator of earliness. Out of 28 F_1 hybrid combinations, 16, 12 and 18 crosses showed negative and favourable heterosis for standard check variety, mid and better parent, respectively. Higher negative mid-parent heterosis (-22.77), better parent (-24.54) and standard check (-

21.23) were observed in Punjab-8 × Kashi Pragati. Negative heterosis for node to first flower appearance and days to first flowering indicated early flowering due to rapid transition from vegetative to reproductive growth. Similar findings have been reported in previous studies (11, 12). For the number of days required for first harvest, the relative heterosis was found to be the minimum in Punjab-8 × Kashi Pragati (-13.61), in which 14 cross combinations showed negative and desirable heterosis over the mid-parent. Similar findings have been reported in previous studies (13). In case of heterobeltiosis, the minimum value for this trait was noted in Pusa Bhindi-5 × Kashi Lalima (-17.88). Heterosis over standard check was recorded at a minimum in Pusa Bhindi-5 × Kashi Lalima (-15.70). Early harvesting may result from early flowering coupled with rapid fruit development, making such parents and hybrids suitable for commercial cultivation. Similar findings have been reported in previous studies, which showed significant and negative standard heterosis for days to first picking (13–15).

In case of fruit length, 8, 4 and 22 out of 28 F_1 hybrids showed significant positive mid-parent heterosis, better parent heterosis and standard check, respectively (Fig. 2). Heterosis over mid-parent was noted maximum in Kashi Chaman × Punjab-8 (16.59). In heterobeltiosis, the maximum value for this trait was found to be in Kashi Chaman × Punjab-8 (16.03). For standard heterosis, the maximum value was Arka Anamika × Prabhani Kranti (49.06).

Table 3. Analysis of variance for heterosis in eleven quantitative parameters

Source of variance	df	Traits										
		First flowering node	Days to first flowering (days)	Days to first picking (days)	Fruit length (cm)	Fruit weight (g)	Fruit diameter (mm)	Number of fruits/plant	Plant height (cm)	Harvest duration (days)	Fruit yield/m ² (kg/m ²)	Fruit yield/plant (q/ha)
Replication	2	0.49	1.36	1.36	0.35	1.42*	0.01*	8.25*	21.51**	10.82**	0.01	0.001
Treatments	36	98.05**	1174.44**	1174.44**	184.09**	188.92**	1.34**	757.13**	59941.68**	4621.98**	3.59**	0.26**
Parents	7	10.66**	204.69**	204.69**	12.47**	19.69**	0.49**	109.69**	10229.57**	1101.10**	0.54**	0.04**
Hybrid	27	82.05**	934.23**	934.23**	156.32**	146.39**	0.63**	633.08**	46661.64**	3406.31**	2.83**	0.21**
Parent vs Hybrid	1	5.24**	19.29**	19.29**	4.23**	9.78**	0.20**	3.30	1371.10**	44.63**	0.08**	0.01**
Check vs Hybrid	1	0.01	19.33**	19.33**	9.81**	11.06**	0.002	9.95**	1412.36**	79.49**	0.12**	0.01**

* and ** significance at $P \leq 0.05$ and $P \leq 0.01$, respectively; df: Degree of freedom.

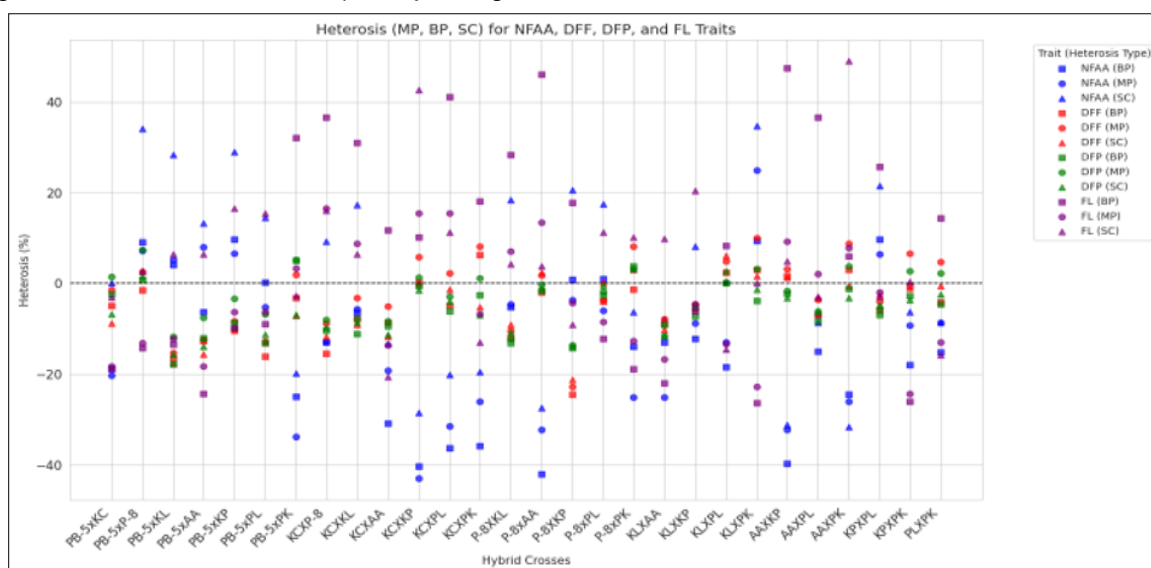


Fig. 2. Heterosis (MP, BP and SC) for First flowering node, days to first flowering, days to first picking and length of fruit. MP = mid-parent; BP = better parent; SC = standard check.

Positive heterosis for fruit length may be attributed to enhanced cell division and cell elongation. Previously reported significant and positive heterosis for this trait. For fruit weight, eight, one and twenty-two hybrid combinations out of 28 showed positive and desirable heterosis (10, 14, 16, 17). In heterosis over mid-parent, the maximum value was observed in Kashi Chaman × Kashi Pragati (11.58). With respect to heterosis over the better parent, the maximum value was noted in Kashi Chaman × Punjab-8 (8.17). Heterosis over the standard check was higher in Arka Anamika × Prabhani Kranti (57.54). The increased fruit weight observed could be due to enhanced photosynthetic efficiency, vigorous plant growth and improved nutrient uptake. These factors promote better fruit development, resulting in heavier fruits. These results corroborate those reported in previous studies (1, 12, 16, 17). Out of 28 hybrid combinations, 16, 11 and 4 exhibited positive and desirable heterosis for fruit diameter, respectively. The highest value in heterosis over mid-parent was found in Kashi Chaman × Punjab-8 (27.19) had the largest heterosis over the better parent. Arka Anamika × Prabhani Kranti had a higher heterosis over the standard check (8.35). Increased fruit diameter is due to enhanced cell and also due to favourable dominant gene attraction. Similar findings have been reported in previous studies (1, 12, 14, 16). The number of fruits/plant showed positive and desirable heterosis in 5, 3 and 15 out of the 28 hybrid combinations. Kashi Chaman × Kashi Pragati had the highest heterosis over the mid-parent value (19.88). The maximum heterosis over the better parent was found in Kashi Chaman × Punjab-8 (12.39), followed by Arka Anamika × Prabhani Kranti (12.66). The heterosis of Arka Anamika × Prabhani Kranti was higher than that of the standard check (40.30). Superior fruit production may have resulted from enhanced flowering, fruit set and reproductive efficiency. Similar findings have been reported in previous studies (14, 16, 18).

For plant height, out of 28 crosses, 16, 10 and 4 crosses showed positive and significant heterosis (Fig. 3). Plant height recorded maximum value in Punjab-8 × Kashi Lalima (49.56) for relative heterosis. In heterobeltiosis, the maximum value was noted in Punjab-8 × Kashi Lalima (46.09). Arka Anamika × Prabhani Kranti (17.20) recorded the highest value among all the crosses over the

standard check, followed by AA × KP (16.04). The increased plant height reflected enhanced hybrid vigour resulting from favourable gene interactions. These results corroborate those reported in previous studies (14, 16, 19).

In harvest duration, out of 28 crosses, 9, 3 and 5 crosses exhibited significant and positive heterosis. For relative heterosis, the maximum value was noted in Kashi Chaman × Kashi Pragati (14.06). For heterosis over better parent, the highest value was exhibited by Kashi Chaman × Punjab-8 (7.49). Arka Anamika × Kashi Pragati (6.51) had shown the maximum value for standard check. The extended harvesting period of both parents and hybrids may be attributed to favourable non-additive gene effects controlling flowering and fruiting duration. Similar findings have been reported in previous studies (17–18). Out of 28 F₁ hybrids, 6, 3 and 19 crosses exhibited significantly positive heterosis over mid-parent, better parent and standard heterosis for fruit yield/m², respectively. Kashi Chaman × Kashi Pragati (32.58) was superior to relative heterosis over mid-parent, followed by Punjab-8 × Arka Anamika (27.16), Kashi Chaman × Punjab-8 (24.93) and Arka Anamika × Prabhani Kranti (15.00). Kashi Chaman × Punjab-8 (21.28) showed superiority over the better parent, followed by Kashi Chaman × Kashi Pragati (10.57) and Arka Anamika × Prabhani Kranti (10.36). For heterosis over standard check, the highest value was noted in Arka Anamika × Prabhani Kranti (121.43). These results corroborate those reported in previous studies (20).

For fruit yield/plant, 6, 2 and 18 crosses out of 28 crosses exhibited positively significant heterosis over mid, better parent and standard check, respectively. Heterosis over mid-parent was recorded highest in Kashi Chaman × Kashi Pragati (31.67), followed by Punjab-8 × Arka Anamika (27.82). Kashi Chaman × Punjab-8 (22.00) showed superiority over the better parent. The standard check was recorded maximum in Arka Anamika × Prabhani Kranti (119.05). The superiority of the best parents and hybrid may be attributed to favourable non-additive gene action, including dominance and overdominance effects, resulting in improved productivity. Similar findings have been reported in previous studies, as shown in Fig. 4 (17, 19).

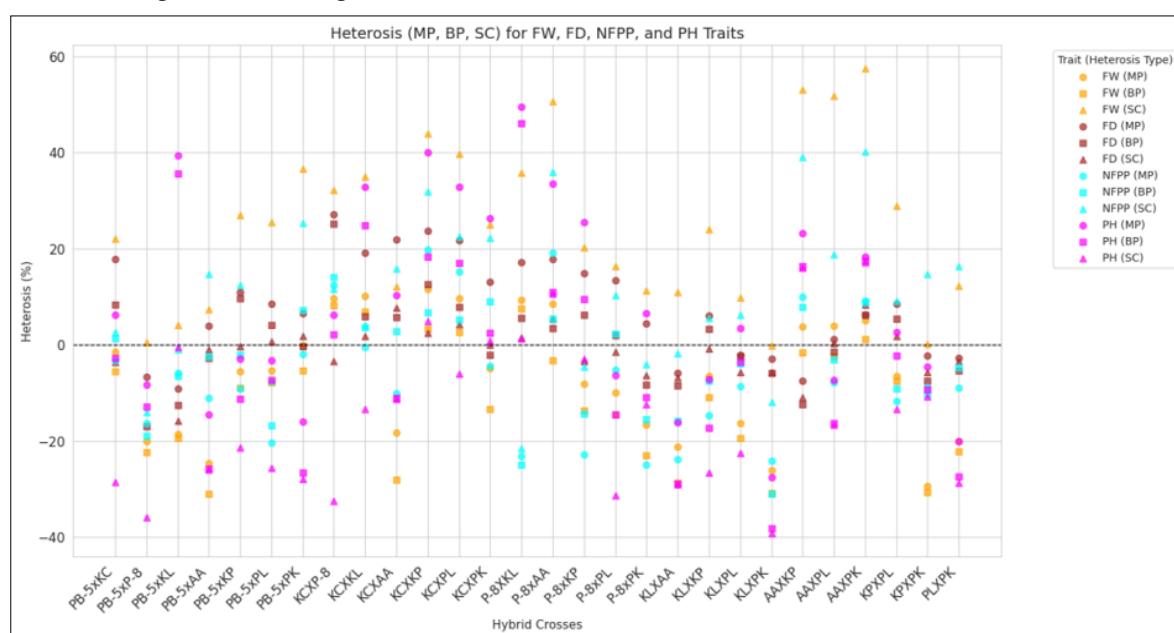


Fig. 3. Heterosis (MP, BP and SC) for weight of fruit, fruit diameter, no. of fruits/plant and plant height.

MP = mid-parent; BP = better parent; SC = standard check.

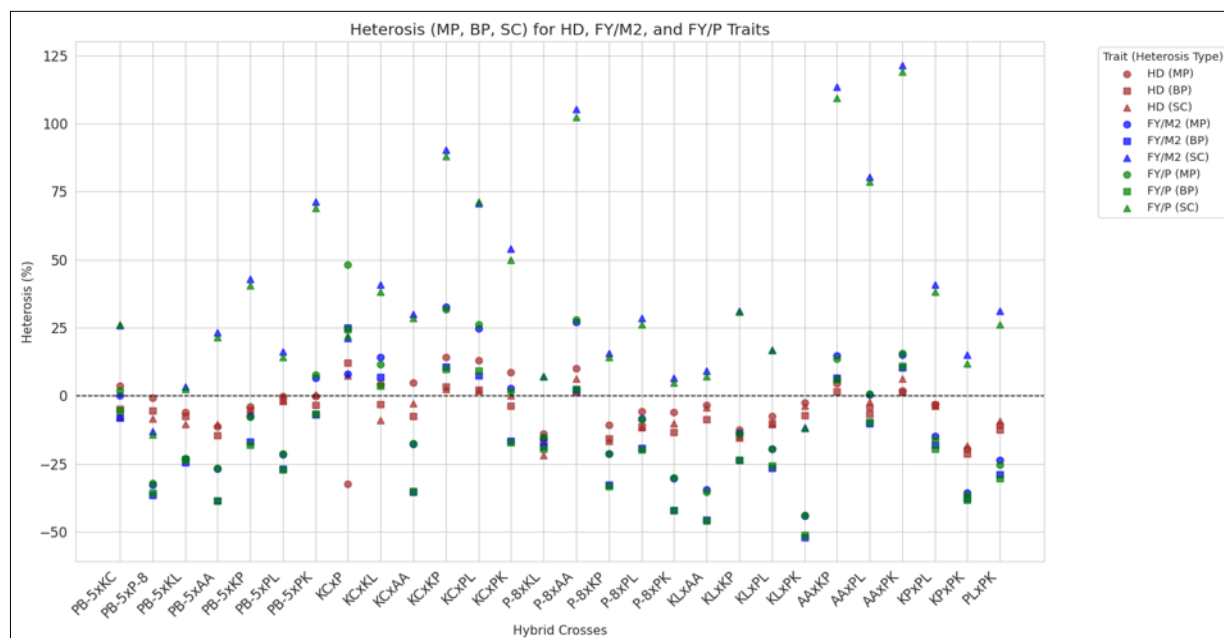


Fig. 4. Heterosis (MP, BP and SC) for harvest duration, fruit yield/m² and fruit yield/plant.

MP = mid-parent; BP = better parent; SC = standard check.

Estimates of general combining Ability effects for parents

The results about general combining ability (GCA) effects are presented in Table 4. For each characteristic evaluated, the mean sum of squares resulting from GCA was highly significant. For the characteristics related to earliness, a GCA in the opposite direction is desirable. As a result, parents who demonstrated significant positive or negative effects on GCA were identified as either good or poor general combiners, respectively. The remaining significant traits exhibited average general combiners. Among the eight parents evaluated, three exhibited significantly negative effects for first flowering node. Arka Anamika (-0.79), Prabhani Kranti (-0.52) and Kashi Chaman (-0.18) indicated significant negative GCA effects, which indicates the existence of good combining ability. Early flowering has been considered as a desirable trait. In days to first flowering, two of the 8 parental lines exhibited negative and significant results and the maximum negative significant effect was noted in Pusa Bhindi-5 (1.67), subsequently followed by Kashi Chaman (-1.28). The significant negative GCA effects observed for earliness traits indicated that these parents possessed favourable additive genes governing early flowering and maturity. Out of the 8 parents, Pusa Bhindi-5 (-2.16), Prabhani Kranti (-2.16) and

Kashi Chaman (-0.60) have been determined to be good combiners because they showed significant negative GCA effects for the number of days to initial picking. With respect to Fruit Length, Arka Anamika (0.80), closely followed by Kashi Pragati (0.28), demonstrated a significant positive GCA effect, indicating that it was the best general combiner for this characteristic. For weight of fruit, good general combiners were Arka Anamika (0.89) and Kashi Pragati (0.27) with significant positive GCA effect. The parental line, Arka Anamika noted as the best combiner for the diameter of fruit (0.06) and harvest duration (5.20). The parents exhibiting significant positive GCA effects for fruit length, fruit diameter and fruit weight possessed a high frequency of favourable additive alleles controlling fruit size. It was found that lines Arka Anamika and Kashi Pragati were positively significant and parents showing strong GCA for the no. of fruits per plant (2.14 and 0.99), plant height (15.64 and 10.47), fruit yield/m² (0.15 and 0.06) and fruit yield/plant (0.04 and 5.65), respectively. The significant positive GCA effects for these traits suggested the predominance of additive gene action. The present findings are in agreement with earlier research. (21–25). Arka Anamika was identified as a good general combiner due to the presence of favourable additive alleles governing the studied traits.

Table 4. Estimation of general combining ability (GCA) of parents for eleven quantitative traits

Parents	First flowering node	Days to first flowering (days)	Days to first picking (days)	Fruit length (cm)	Fruit weight (g)	Fruit diameter (mm)	Number of fruits/plant	Plant height (cm)	Harvest duration (days)	Fruit yield/m ² (kg/ m ²)	Fruit yield/plant (q/ha)
Pusa Bhindi-5	0.52**	-1.67**	-2.16**	-0.73**	-0.4 **	-0.04**	-0.96**	-11.34**	-0.10	-0.07**	-0.02**
Kashi Chaman	-0.18**	-1.28**	-0.60**	0.14	0.05	-0.02*	0.08	-3.03**	-0.89**	0.003	0.001
Punjab-8	0.40**	0.90**	0.98**	-0.11	-0.24**	-0.06**	-1.53**	-4.08**	-3.75**	-0.07**	-0.02**
Kashi Lalima	0.55**	-0.15	0.25	-0.44**	-0.55**	-0.01	-1.94**	-7.16**	-3.31**	-0.11**	-0.03**
Arka Anamika	-0.79**	-0.06	-0.30	0.80**	0.89**	0.06**	2.14**	15.64**	5.20**	0.15**	0.04**
Kashi Pragati	0.04	0.16	0.22	0.28**	0.27**	-0.01	0.99**	10.07**	-0.24	0.06**	0.02**
PunjabLalima	-0.01	1.78**	1.40**	0.07	0.12	0.03**	0.17	-6.04**	1.08**	0.01	0.003
Prabhani Kranti	-0.52**	0.30**	-2.16**	-0.02	-0.08	0.034**	1.04**	5.95**	2.02 **	0.04**	0.009**

* and ** significance at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Estimates of specific combining ability effects for F_1

The results about SCA effects are presented in Table 5. Among the 28 F_1 hybrids, only twelve exhibited significantly negative specific combining ability (SCA) effects for the first flowering node, where Kashi Chaman $\times$ Kashi Pragati (-1.42) had the maximum negative SCA effect. Twelve out of 28 hybrids showed significantly negative SCA effects for earliest flowering and the hybrid combination Punjab-8 $\times$ Kashi Pragati (-9.04) had the highest negative SCA effect, followed by Pusa Bhindi-5 $\times$ Kashi Lalima (-4.43) and Pusa Bhindi-5 $\times$ Arka Anamika (-3.52). For the character days to first picking, eleven hybrid combinations showed negatively significant SCA effect. The best performing cross for this trait was noted in

Punjab-8 $\times$ Kashi Pragati (-5.91), Pusa Bhindi-5 $\times$ Kashi Lalima (-4.43) and Pusa Bhindi-5 $\times$ Arka Anamika (-2.39). Nine cross combinations were found to have a significant and positive SCA effect in fruit length. The superior cross combination was found to be in Pusa Bhindi-5 $\times$ Prabhani Kranti (1.64), followed by Arka Anamika $\times$ Prabhani Kranti (1.61). In fruit weight, 16 cross combinations were found to be positively significant and the maximum value for this trait was noted in Arka Anamika $\times$ Prabhani Kranti (1.60). A total of 15 hybrid combinations demonstrated positively significant SCA effect for fruit diameter and the best cross was observed in Punjab-8 $\times$ Kashi Lalima (0.14), followed by Kashi Chaman $\times$ Arka Anamika (0.12) and Kashi Chaman $\times$ Kashi Pragati (0.11). The present findings are in agreement with earlier research (22, 26).

Table 5. Estimation of specific combining ability of parents for eleven quantitative traits

Hybrids	First flowering node	Days to first flowering (days)	Days to first picking (days)	Fruit length (cm)	Fruit weight (g)	Fruit diameter (mm)	Number of fruits/plant	Plant height (cm)	Harvest duration (days)	Fruit yield/m ² (kg/m ²)	Fruit yield/plant (q/ha)
Pusa Bhindi-5 $\times$ Kashi Chaman	-0.52**	1.03**	1.91**	-1.62**	0.05	0.05*	-0.60	-4.59**	-1.12*	-0.02	-0.002
Pusa Bhindi-5 $\times$ Punjab-8	0.55**	4.45**	4.87**	-0.88**	-1.37**	-0.10**	-1.92**	-14.72**	1.29*	-0.14**	-0.04**
Pusa Bhindi-5 $\times$ Kashi Lalima	0.13	-4.43**	-3.87**	-0.23	-0.77**	-0.14**	0.80	41.93**	-0.81	-0.02	-0.01
Pusa Bhindi-5 $\times$ Arka Anamika	0.74**	-3.52**	-2.39**	-1.45**	-1.95**	0.02	-0.54	-19.43**	-9.39**	-0.18**	-0.05**
Pusa Bhindi-5 $\times$ Kashi Pragati	0.67**	-1.21**	-0.45	-0.03	0.20	0.09**	0.21	-6.87**	-0.05	0.02	0.004
Pusa Bhindi-5 $\times$ Punjab Lalima	0.01	-4.09**	-2.55**	0.08	0.25	0.07**	-2.46**	2.80**	2.22**	-0.07**	-0.02**
Pusa Bhindi-5 $\times$ Prabhani Kranti	-1.16**	0.25	1.03*	1.64**	1.32**	0.08**	2.43**	-12.50**	3.20**	0.18**	0.05**
Kashi Chaman $\times$ Punjab-8	0.05	-3.00**	-2.90**	1.26**	0.61*	0.07**	1.56**	-17.71**	4.55**	0.10**	0.03**
Kashi Chaman $\times$ Kashi Lalima	0.30	-0.69*	-1.57**	1.08**	1.14**	0.10**	0.65	14.13**	1.07*	0.10**	0.02**
Kashi Chaman $\times$ Arka Anamika	0.14	-2.04**	-2.48**	-1.85**	-2.10**	0.12**	-1.36**	-5.55**	-2.02**	-0.22**	-0.06**
Kashi Chaman $\times$ Kashi Pragati	-1.42**	3.41**	2.46**	1.41**	1.02**	0.11**	2.61**	24.36**	8.23**	0.19**	0.05**
Kashi Chaman $\times$ Punjab Lalima	-0.97**	1.19**	-0.11	1.48**	0.85**	0.10**	1.78**	23.97**	6.36**	0.13**	0.04**
Kashi Chaman $\times$ Prabhani Kranti	-0.43**	0.80*	-0.53	-0.46	-0.11	0.03	0.84	22.35**	3.79**	0.02	0.003
Punjab-8 $\times$ Kashi Lalima	-0.23	-2.87**	-4.34**	1.09**	1.49**	0.14**	-2.27**	37.35**	-7.37**	0.01	0.002
Punjab-8 $\times$ Arka Anamika	-1.13**	2.65**	1.61**	1.43**	1.22**	0.13**	3.78**	28.59**	8.86**	0.24**	0.07**
Punjab-8 $\times$ Kashi Pragati	0.38*	-9.04**	-5.91**	-0.55*	-0.55*	0.06**	-2.20**	13.71**	-5.67**	-0.12**	-0.03**
Punjab-8 $\times$ Punjab Lalima	0.28	-0.19	0.31	-0.91**	-0.71**	0.06*	1.24*	-13.10**	-2.64**	-0.01	-0.003
Punjab-8 $\times$ Prabhani Kranti	-0.37*	2.62**	3.83**	-0.92**	-0.91**	-0.02	-2.17**	3.51**	-2.26**	-0.15**	-0.04**
Kashi Lalima $\times$ Arka Anamika	-0.32*	-2.37**	-2.13**	-1.45**	-1.59**	-0.10**	-2.45**	-28.28**	-0.67	-0.21**	-0.06**
Kashi Lalima $\times$ Kashi Pragati	-0.37*	-0.33	-0.19	0.0004	0.06	0.06*	-0.01	-19.01**	-5.26**	-0.0003	0.0004
Kashi Lalima $\times$ Punjab Lalima	-0.70**	3.72**	2.71**	-0.86**	-0.92**	-0.05*	0.94	3.26**	-2.08**	-0.03	-0.007
Kashi Lalima $\times$ Prabhani Kranti	1.48**	3.00**	1.69**	-1.50**	-1.49**	-0.04	-3.14**	-33.81**	2.99**	-0.20**	-0.05**
Arka Anamika $\times$ Kashi Pragati	-0.95**	2.85**	1.23*	1.18**	0.90**	-0.16**	1.80**	22.45**	5.68**	0.15**	0.04**
Arka Anamika $\times$ Punjab Lalima	0.20	-1.03**	-1.61**	0.42	0.95**	-0.03	-0.94	-10.61**	-3.28**	0.03	0.01
Arka Anamika $\times$ Prabhani Kranti	-0.41**	1.85**	1.1726*	1.61**	1.60**	0.08**	1.97**	28.32**	3.23**	0.21**	0.06**
Kashi Pragati $\times$ Punjab Lalima	0.84**	-0.79*	-1.40**	-0.03	-0.23	0.05*	-1.50**	-0.03	0.85	-0.08**	-0.02**
Kashi Pragati $\times$ Prabhani Kranti	-0.01	1.43**	0.45	-2.17**	-2.29**	-0.07**	-1.38**	-8.16**	-12.99**	-0.24**	-0.06**
Punjab Lalima $\times$ Prabhani Kranti	-0.08	0.01	-0.06	-0.73**	-1.19**	-0.07**	-0.27	-19.05**	-6.31**	-0.11**	-0.03**

* and ** significance at $P \leq 0.05$ and $P \leq 0.01$, respectively.

For the number of fruits/plant, the best cross combination, Punjab-8 × Arka Anamika (3.78) for this trait, showed significantly positive SCA effect. Among all the crosses, eight are found to be significant and desirable. In plant height, 13 hybrid combinations showed positively significant SCA effect and the best-performing cross was noted in Pusa Bhindi-5 × Kashi Lalima (41.93), closely followed by Punjab-8 × Arka Anamika (28.59) and Arka Anamika × Prabhani Kranti (28.32). Twelve crosses showed a significant and positive SCA effect for harvest duration and the maximum value was recorded in Punjab-8 × Arka Anamika (8.86). For fruit yield/m², 8 crosses exhibited positively significant SCA effect and the best-performing cross was found to be in Punjab-8 × Arka Anamika (0.24). Among the hybrids, eight crosses showed significantly positive SCA effect for fruit yield/plant and the maximum value was recorded in Punjab-8 × Arka Anamika (0.07). The superior SCA effects observed in the promising hybrids indicated the predominance of non-additive gene action involving dominance and epistatic effects. Hence, these crosses are suitable for exploiting heterosis. Research has reported similar findings (22, 26, 27).

Estimation of gene action

Table 6 presents the results related to gene action. For each trait, the specific combining ability variance (σ^2_{SCA}) was greater than the mean general combining ability variance (σ^2_{GCA}), which indicates that non-additive gene action primarily controls all of the studied traits. The ratio of GCA to SCA was found to be less than unity for each quantitative trait investigated; this suggests that non-additive gene action plays a predominant role in the inheritance of these traits. Further support for these results was provided by the estimation of additive (σ^2_A) and dominance (σ^2_D) variance components, where dominance variance was consistently higher than additive variance for all traits except one trait. Furthermore, the variance ratio (σ^2_A / σ^2_D) for each character under investigation was less than one, indicating that the dominant variance predominates in the expression of these attributes. According to broad-sense heritability estimates, the traits under study had a significant heritable potential ($\geq 50\%$). However, narrow-sense heritability values were typically low ($< 50\%$), suggesting that non-additive genetic effects were predominant in governing these characteristics. The predominance of non-additive gene action indicated that dominance and epistatic effects are primarily responsible for the inheritance of these traits. Research also reported similar findings about the inheritance of major yield and yield-contributing characters, emphasizing the existence of non-additive gene action for the majority of characteristics (12, 24).

Table 6. Gene action of quantitative traits in okra

	First Flowering Node	Days to First Flowering (Days)	Days to First Picking (Days)	Fruit Length (cm)	Fruit Weight (g)	Fruit Diameter (mm)	Number of Fruits/Plant	Plant Height (cm)	Harvest Duration (Days)	Fruit yield/m ² (kg/m ²)	Fruit Yield/Plant (q/ha)
σ^2_{GCA}	0.23	1.20	1.14	0.20	0.20	0.002	1.93	89.04	8.28	0.007	0.001
σ^2_{SCA}	0.54	10.60	7.46	1.47	1.49	0.01	3.67	470.18	33.11	0.02	0.002
$\sigma^2_{GCA} / \sigma^2_{SCA}$	0.43	0.11	0.15	0.14	0.14	0.12	0.53	0.19	0.25	0.34	0.33
PR	0.46	0.19	0.23	0.22	0.21	0.21	0.51	0.275	0.33	0.41	0.40
Σ^2_a variance	0.47	2.41	2.27	0.40	0.40	0.003	3.87	178.09	16.56	0.02	0.001
Σ^2_d variance	0.54	10.60	7.46	1.47	1.49	0.01	3.67	470.18	33.12	0.02	0.002
H ² broad sense (%)	97.37	98.93	97.05	96.62	96.14	95.87	96.15	99.90	99.40	97.64	97.47
H ² narrow sense (%)	45.21	18.33	22.66	20.82	20.49	19.68	49.29	27.44	33.13	39.52	38.54

GCA = general combining ability; SCA = specific combining ability; PR = predictability ratio; σ^2_A (Σ^2_a) = additive genetic variance; σ^2_D (Σ^2_d) = dominance genetic variance; H² = heritability.

The present investigation was conducted under a single environmental condition with uniform agronomic practices; therefore, the observed variation in yield and related traits is largely attributable to genetic differences among the parental lines and hybrids. However, as quantitative traits are influenced by genotype × environment interaction, further evaluation across multiple locations and seasons is required to confirm the stability of the identified superior genotypes.

Conclusion

The Present study identified Arka Anamika, Prabhani Kranti and Kashi Pragati as superior general combiners, indicating their potential as valuable parental lines for developing high-yielding and early maturing okra cultivars. Among the hybrids, Arka Anamika × Prabhani Kranti, Arka Anamika × Kashi Pragati and Punjab-8 × Arka Anamika and Pusa Bhindi-5 × Arka Anamika consistently exhibited superior performance for earliness and yield-related traits, suggesting their utility for the development of productive and early maturing hybrids. The predominance of non-additive gene action suggests that heterosis breeding is an effective strategy for improving okra productivity. These hybrids may be considered for multilocation evaluation and commercial hybrid development. The finding provides a practical framework for breeders to select elite parents and hybrid combinations for accelerating okra improvement programmes and future studies integrating molecular breeding approaches may further enhance the efficiency of hybrid development.

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Authors' contributions

H conceived the study, carried out the formal analysis and investigation and drafted the original manuscript. YSB guided the experiment and contributed to data analysis. AS contributed to writing and editing. MA helped in contributed in creating figures and tables. ASR provided materials, equipment, or expertise. DK contributed to reviewing and editing. AK contributed in Final reviewing and corrections. R contributed to editing the manuscript.

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Compliance with ethical standards

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