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Genetic studies on heterosis estimation and combining ability analysis in bhendi (*Abelmoschus esculentus*)

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Abstract
The present study was conducted during 2024 bhendi growing seasons at the campus farm, Department of Agriculture, Kalasalingam Academy of research and Education, Krishnan koil. A thorough investigation into the genetic regulation of eight agronomically significant features in the target crop was carried out utilising a 7-parent diallel mating design with reciprocals. Both additive and non-additive gene actions significantly influenced the inheritance of all the traits under study, according to the analysis of variance (ANOVA) for general combining ability (GCA) and specialised combining ability (SCA). This implies that both additive and non-additive gene effects—those that depend on particular parental combinations and those that are passed on from parents to children in a predictable way—play important roles in the development of traits. Strong general combining ability effects were demonstrated by a number of parents, indicating their potential application in hybridisation programs intended to accumulate advantageous alleles. The Varsha Uphar × Madurai local hybrid showed remarkable per se performance, high SCA effects, and significant standard heterosis for most of the characteristics, suggesting a high potential for commercial exploitation among the hybrids assessed. The hybrid vigour found in these pairings was further highlighted by the hybrid Varsha Uphar × Tenksi local, which recorded the highest standard heterosis for fruit output per plant at 78.56%.

Keywords: Bhendi, combining ability, heterosis, diallel analysis, hybrid, Diallele analyses

Introduction
A vital vegetable crop grown throughout India and other tropical regions, Bhendi (*Abelmoschus esculentus*) is essential to both food security and farmer incomes. Enhancing the sustainability and productivity of bhendi production has emerged as a major area of attention for agricultural development initiatives due to the fast increase in the demand for vegetables worldwide Singh, A. & Pandey, M. K. 2024 [11]. In response, the creation of high-yielding, disease-resistant hybrids that can adapt to a variety of agroclimatic situations is becoming a top priority for plant breeders.

The two main genetic concepts that drive hybrid breeding are heterosis and combining ability. The ability of parental lines to create hybrids with desired characteristics including increased yield, disease and insect resistance, and improved nutritional quality is known as "combining ability." Begna, T. (2021) [1]. The phenomena whereby hybrid offspring outperform their parents in traits like growth rate, yield potential, and stress tolerance is known as heterosis, or hybrid vigour.

Ability and heterosis are two basic genetic concepts that drive hybrid breeding. Combining ability is the ability of parental lines to create hybrids with desired characteristics including increased nutritional value, resistance to pests and diseases, and greater yield. T. Begna. 2021[1]. The phenomenon known as heterosis, or hybrid vigour, occurs when hybrid offspring outperform their parents in characteristics such as growth rate, yield potential, and stress tolerance.

Although hybrid breeding has advanced significantly, there are still a number of obstacles to overcome. The limited availability of genetically diverse parental lines is a significant drawback that may limit the possibility of attaining high combining ability and heterotic response (Singh, R. & Singh, S. 2023) [12]. Furthermore, a more thorough investigation of the genetic and molecular mechanisms underlying complex features like improved drought tolerance or resistance to particular diseases is required in order to produce hybrids with these qualities.

This article aims to present a thorough analysis of the state of the art concerning the combination of heterosis and ability in hybrid bhendi. Key discoveries, difficulties, and future directions for this field of study will be discussed. Through the investigation of intricate relationships between parent lines and hybrids, we may fully utilise hybrid breeding and produce superior bhendi types that are advantageous to both farmers and consumers.

Materials and Methods

During the 2024 bhendi growing seasons, the experimental study was carried out at the Campus Farm, Kalasalingam School of Agriculture and Horticulture, KARE. In 2024, a diallel mating pattern was created by crossing seven bhendi lines: Arka Anamika, Madurai Local, Virudhunagar Local, Parbhani Kranti, Tenkasi Local, Lakshmi 1, and Villupuram Local.

During the trial, every suggested agronomic technique and plant protection measure under irrigated conditions was adhered to. Plants were spaced 30 cm apart and rows were spaced 60 cm apart. Data on yield and yield component features, including plant height, number of branches per plant, fruit length, fruit weight, number of fruits per plant, number of seeds per fruit, and internode distance, were recorded for randomly chosen plants per entry every replication. In 2024, 42 hybrids' F1 seeds, seven parents, and a typical check hybrid Varsha Uphar were raised. In order to maintain 10 plants in each row, 30 crossings were cultivated in two replications using a randomised block design (RBD). Each cross was placed in two rows, each measuring 6 m in length, with a 90 cm gap between rows and a 60 cm gap between plants. To evaluate their combining capacity, the parents were also raised in the nearby block with four rows for each entry, spaced 90 x 45 cm apart, along with a typical check hybrid.

Five plants were chosen at random from each genotype in each replication to assess important biometrical characteristics. Plant height, internode length, fruit length, number of seeds per fruit, number of branches per plant, number of fruits per plant, average fruit weight, and fruit yield per plant were among the traits evaluated. The TNAUSTAT software program was used to statistically analyse the mean data from parents, hybrids, and standard checks for heterosis and combining ability.

Replication and treatment caused each of the seven traits' total variation to be divided into components. In order to facilitate comprehension and debate, yield-related characteristic data were methodically tabulated, and the analysis of variance (ANOVA) results were provided together with estimates of standard error and critical difference (CD). Additionally, standard heterosis values were computed by comparing them to check hybrids. The TNAUSTAT software was used for all statistical calculations.

Results and Discussions

Significant genetic variety between the parent plants and their 42 hybrid combinations was revealed by the analysis of variance (Table 1). With a significantly better fruit output per plant than the parental average, P1 outperformed P5, P6, and P4 among the seven parents under study, making them excellent choices for crossbreeding initiatives. (Table 2).

In terms of fruit yield, 18 of the 42 hybrids—both direct and reciprocal—outperformed the hybrid mean. The hybrids P2 × P5, P2 × P6, P4 × P2, P5 × P4, P4 × P5, P6 × P3, and P7 × P3 were notable for their remarkable yields, which reached about 550g per plant (Table 5). These hybrids show great promise since they are the result of crossings in which at least one parent line has advantageous features or both parent lines performed well in terms of yield. This finding is in line with recent research that highlights the importance of parental selection in maximising hybrid performance and yield-related traits, such as that conducted by Waikhom Jupiter Singh *et al.* (2022) [16] and Janarthanan & Sundaram (2020) [3].

The efficacy of high-yield hybrids in breeding selection was further supported by the fact that they continuously displayed important beneficial features, such as more fruits per plant, more branching, and higher average fruit weight.

With the exception of internodal distance, days to fruit maturity, fruit girth, and number of branches per plant, the analysis of combining ability variances showed substantial differences in general combining ability (GCA) and specialised combining ability (SCA) for the majority of variables (Table 4). This implies that both additive and non-additive genetic variance are present in the inheritance of traits. For the majority of traits, the GCA/SCA ratio was noteworthy because it was greater than unity. This suggests that additive genetic variance has a significant impact on important traits like the number of days until the first flowering, plant height, internodal distance, number of immature seeds per fruit, number of branches per plant, fruit girth, and number of fruits per plant. On the other hand, days to fruit maturity, fruit length, average fruit weight, and total fruit production were all significantly influenced by non-additive genetic variance.

Similar results have been observed in recent research, such as those by Vinithra *et al.* (2019) [15], Sundaram *et al.* (2020) [3], and Shwetha *et al.* (2022) [9], supporting the genetic basis of these features. While non-additive genetic variance might be better utilised in subsequent generations, the presence of additive genetic variance implies that improvement techniques like pure line selection or pedigree selection could successfully enhance desired traits. For better bhendi breeding results, a combination strategy that includes population improvement initiatives could maximise both variance types.

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Reciprocal recurrent selection in a population improvement program would be the most successful hybrid development technique due to the existence of reciprocal differences across several attributes. This strategy maximises hybrid performance and guarantees long-term genetic gains by enabling the simultaneous exploitation of additive and non-additive genetic variance.

Relationship between per se performance and combining ability effects

P1, P5, P6, and P4 were the parental lines that showed the strongest GCA effects across a variety of attributes among those studied. In particular, P1 showed favourable GCA impacts for average fruit weight, fruit length, number of branches per plant, and days to first flowering. Days to initial flowering, plant height, internode distance, number of immature seeds per fruit, and fruit girth were all positively impacted by GCA in P5. Days to fruit maturity, the number of immature seeds per fruit, and the number of branches per plant were all positively impacted by P6. With positive GCA effects for internode distance, days to fruit maturity, number of branches per plant, fruit length, average fruit weight, and fruit yield per plant, P4 stood up as a superior combiner (Table 2).

Interestingly, P4 was the only parent with both high yield and positive GCA effects, whereas P1, P5, and P6 recorded high fruit yield per plant but showed negative GCA effects for fruit yield. P4 was the top combiner when evaluating total GCA performance, followed by P5 and P7. P5 and P4 are excellent prospects for varietal breeding programs due to their outstanding per se performance and high GCA effects, which indicate significant additive genetic variability.

Nine hybrids (P1 × P3, P2 × P5, P2 × P6, P4 × P2, P4 × P5, P5 × P4, P6 × P3, P6 × P7, and P7 × P3) showed substantial positive SCA impacts on fruit yield per plant out of the 18 hybrids that outperformed the hybrid mean in fruit yield. Notably, hybrids with the highest mean fruit output per plant, including P2 × P5, P2 × P6, P4 × P2, P5 × P4, P4 × P5, P6 × P3, and P7 × P3, also showed positive SCA effects across a number of characteristics, including fruit yield per plant.

Current research on heterosis in bhendi hybrids has reaffirmed how important specific combining ability (SCA) is for increasing production. Along with beneficial SCA effects for important traits as average fruit weight, fruit length, number of fruits per plant, and number of branches per plant, the hybrids P2 × P5, P4 × P5, and P4 × P5 showed the highest mean fruit output per plant. P6 × P3 demonstrated favourable SCA effects for fruit yield per plant and number of fruits per plant, but P4 × P2, P2 × P6, and P7 × P3 displayed strong SCA effects for fruit yield per plant and average fruit weight (Table 4).

The hybrids P2 × P5, P6 × P7, P1 × P3, P1 × P4, P3 × P7, P4 × P5, P5 × P7, P2 × P4, and P2 × P7 were shown to be good specific combiners when evaluating overall SCA performance across eleven variables. Furthermore, P2 × P5, P4 × P2, P2 × P6, P7 × P3, and P5 × P4 showed favourable heterobeltiosis for fruit output per plant, with the exception of fruit length, fruit girth, and the number of branches per plant.

These results are consistent with recent studies by Waikhom Jupiter Singh *et al.* (2022) [16], which highlight the significance of hybrid selection based on SCA effects and heterosis. Recent studies have emphasised the significance of standard heterosis among the three types of heterosis in maximising hybrid vigour.

In terms of fruit output per plant, the hybrids P2 × P5 (79.16%), P2 × P6 (45.15%), P4 × P2 (45.04%), P5 × P4 (35.71%), and P4 × P5 (34.88%) showed the highest standard heterosis, exceeding 35%. With the exception of plant height, fruit length, and fruit girth, these hybrids likewise showed good standard heterosis across the majority of characteristics. Furthermore, hybrids with high standard heterosis for fruit production per plant also have standard heterosis of about 25% for number of fruits per plant, another important productive feature.

These results are consistent with recent studies that highlight the function of hybrid selection based on heterosis effects, such as those conducted by Siva Ranjani *et al.* (2020) [13], Johnny Subakar Ivin & Anbuselvam (2021) [6], and Ebenezer Babu Rajan *et al.* (2022) [2]. Recent research have emphasised the significance of conventional heterosis in optimising hybrid vigour, hence reaffirming its applicability in bhendi breeding initiatives.

Table 1: ANOVA for fruit yield and yield component characters in bhendi

Sl. No.	Characters	MSS	'F' value
1.	Plant height	1414.94**	198.51
2.	Internode distance	3.08**	11.41
3.	Number of seeds per fruit	103.25**	12.97
4.	Fruit length	13.65**	127.8
5.	Number of branches per plant	1.84**	64.64
6.	Number of fruits per plant	39.2**	20.87
7.	Average fruit weight	33.85**	22.97
8.	Fruit yield per plant	28719.93**	73.63

**-Significant at 1 percent level

*-Significant at 5 percent level

Table 2: Estimates of variance for combining ability

Sources	Mean Sum of Squares							
	Plant height	Inter node distance	Number of seeds per fruit	Fruit length	Number of branches per plant	Number of fruits per plant	Average fruit weight	Fruit yield per plant
GCA	500.79**	1.02	55.09**	0.87	0.15	21.1**	8.58**	4860.33**
SCA	445.9**	0.45	28.16**	4.29**	0.03	10.49**	11.53**	7859.12**
Reciprocal variance	485.66**	0.55	25.02**	5**	0.05	17.33**	18.06**	13384.03**
GCA/SCA	1.12	2.27	1.96	0.20	5	2.01	0.74	0.62

Table 3: Performance of the best five crosses selected for fruit yield per plant based on heterobeltiosis (d_{ii}), for other traits in percent

S. No.	Characters	P_2 x P_5 d_{ii} = 81.31**	P_4 xP_2 d_{ii} = 61.68	P_2 xP_6 d_{ii} = 47.81	P_7x P_3 d_{ii} = 41.25	P_5x P_4 d_{ii} = 37.16**
1.	Plant height	40.38**	-16.33**	29.93**	-16.78**	-11.07**
2.	Internode distance	-23.79**	-0.89	7.9*	7.23*	-5.88
3.	Number of seeds per fruit	-4.2	3.09	11.04	-0.5	-18.29**
4.	Fruit length	0.73**	-38.69**	0.35**	-11.79**	-3.16**
5.	Number of branches per plant	0.51	-26.82	0.13	14.33**	-0.19
6.	Number of fruits per plant	54.2**	4.33*	8.06**	10.40	13.23**
7.	Average fruit weight	9.79**	31.45**	36.4**	22.06	-9.87*

** -Significant at 1 percent level

* -Significant at 5 percent level

Table 4: Relationship between *per se* performance and *gca* effects

Sl. No.	Characters	*per se* performance	*gca* effects	Common parent
1.	Plant height	P_2 (83.00)	P2	P2
		P_3 (104.66)	P5	P3
		P_1 (106.33)	P3	-
2.	Internode distance	P_5 (7.86)	P5	P5
		P_3 (8.89)	P3	P3
		P_7 (9.90)	P4	-
3.	Number of seeds per fruit	P_5 (45.47)	P6	P5
		P_6 (52.95)	P7	P6
		P_3 (54.49)	P5	-
4.	Fruit length	P_1 (19.03)	P4	P1
		P_5 (17.63)	P1	-
		P_2 (16.07)	2	P2
5.	Number of branches per plant	P_3 (6.00)	P7	-
		P_4 (6.00)	P1	-
		P_6 (6.00)	P6	P6
6.	Number of fruits per plant	P_5 (25.33)	P4	-
		P_7 (24.63)	P7	P7
		P_6 (24.00)	-	-
7.	Average fruit weight	P_5 (25.40)	P2	P2
		P_1 (23.80)	P4	-
		P_2 (20.80)	P1	P_1
8.	Fruit yield per plant	P_1 (380.12)	P4	P_4
		P_5 (373.40)	P7	-
		P_6 (370.60)	-	-
		P_4 (366.23)	-	-

*-Significant at 5 percent level
**-Significant at 1 percent level

Table 5: Relationship between *per se* performance, standard heterosis (d_{iii}), *sca* effects/ reciprocal effects and *gca* effects

Characters	Best five crosses with high per se	Best five crosses with high d_{iii}	Common crosses	*sca* / reciprocal effects	*gca* effects
Plant height	P_6 x P_2 (81.33)	P6 x P2	P_6 x P_2	1.57 / 36.78**	4.56** x-5.67**
	P_5 x P_6 (90.5)	P5 x P6	P_5 x P_6	-11.63** /-14.89**	-4.97** x 4.56**
	P_2 x P_3 (93.00)	P2 x P3	P2 x P3	-4.38** /-9.47**	-5.67** x-4.9**
	P_3 x P_5 (93.00)	P3 x P5	P3 x P5	-9.25** /-5.3**	-4.9** x-4.97**
	P_3 x P_7 (93.00)	P3 x P7	P3 x P7	-12.45** /-11.56**	-4.9** x 4.48**
Internode distance	P_6 x P_3 (7.66)	P6 x P3	P_6 x P_3	-0.32** / 1.83**	0.35** x-0.16**
	P_5 x P_3 (8.05)	P5 x P3	P_5 x P_3	-9.25** / 0.88**	-0.3** x-0.16**
	P_2 x P_7 (8.21)	P2 x P7	P2 x P7	-0.9** /-0.56**	0.22 x 0.2
	P_2 x P_5 (8.38)	P2 x P5	P2 x P5	-0.15* /-0.78**	0.22 x-0.3**
	P_3 x P_1 (8.83)	P3 x P1	P3 x P1	0.51 / 1.35**	-0.16** x 0.57**
Number of seeds per fruit	P_2 x P_7 (44.00)	P2 x P7	P2 x P7	-5.15** /-5.25**	0.97* x-1.23**
	P_6 x P_1 (44.09)	P6 x P1	P_6 x P_1	-4.71** / 7.95**	-2.29** x 4.15**
	P_5 x P_6 (45.06)	P5 x P6	P5 x P6	-5.33** /-1.35	-0.64* x-2.29**
	P_6 x P_5 (47.97)	P6 x P5	P_6 x P_5	-5.33** /-1.35	-2.29** x-0.64*
	P_4 x P_7 (48.71)	P4 x P7	P_4 x P_7	-0.64 /-4.29**	-0.17 x-1.23**
Fruit length	P_4 x P_3 (21.33)	P4 x P3	P_4 x P_3	2.71** /-3.43**	0.46** x 0.05*
	P_7 x P_2 (20.2)	P7 x P2	P_7 x P_2	1.8** /-3.15**	0.12 x 0.22*
	P_2 x P_3 (18.33)	-	-	-	-
	P_2 x P_5 (17.66)	-	-	-	-
	P_4 x P_1 (17.36)	-	-	-	-
Number of branches per plant	P_1 x P_3 (6.80)	P1 x P3	P1 x P3	0.37** / 1.01**	0.22** x-0.01**
	P_7 x P_4 (6.66)	P7 x P4	P_7 x P_4	-0.06** /-0.72**	0.39** x 0.2**
	P_6 x P_1 (6.40)	P7 x P3	-	0.51** /-0.09**	0.39** x-0.01**
	P_7 x P_3 (6.40)	P7 x P1	-	0.07 /-0.22**	0.39* x 0.22**
	P_7 x P_1 (6.33)	P4 x P6	-	-	-
Number of fruits per plant	P_2 x P_5 (30.66)	P2 x P5	P2 x P5	4.95** / 3.61**	-0.74** x-0.3*
	P_6 x P_3 (30.33)	P6 x P3	P_6 x P_3	2.34** /-5.22**	0.05 x-0.65**
	P_6 x P_7 (30.33)	P6 x P7	P_6 x P_7	1.14* / 3.78**	0.05 x 0.21**
	P_4 x P_7 (30.00)	P4 x P7	P4 x P7	0.12 / 3.28**	1.24** x 0.21**
	P_7 x P_1 (30.00)	P7 x P1	P_7 x P_1	1.1* /-4.22**	0.21** x-0.91**
Average fruit weight	P_2 x P_3 (29.33)	P2 x P3	P2 x P3	-0.2 / 7.99**	1.07* x 0.1
	P_2 x P_5 (27.48)	P7 x P1	-	-	-
	P_2 x P_6 (27.26)	P2 x P5	-	0.89* / 5.44**	1.07** x-0.29**
	P_4 x P_3 (26.68)	P2 x P6	-	2.47** / 3.69**	1.07 x-0.33**
	P_4x P_2 (26.43)	P4 x P3	-	0.88* /-4.48**	0.63** x 0.1
Fruit yield per plant	P_2 x P_5 (678.64)	P2 x P5	P2 x P5	119.14** / 195.29**	4.89 x-12.43**
	P_2 x P_6 (550.60)	P2 x P6	P_2 x P_6	20.53** / 164.65**	4.89 x-11.43**
	P_4 x P_2 (549.96)	P_4 x P_2	P_4 x P_2	32.88** /-108.31**	31.91** x 4.89
	P_5x P_4 (514.80)	P5 x P4	P5 x P4	121.88** /-1.46	-12.43** x 31.91**
	P_4 x P_5 (511.66)	P4 x P5	P4 x P5	121.88** /-1.46	31.91** x-12.43**
	P_6 x P_3 (503.03)	P6 x P3	P6 x P3	51.91** /-104.72**	-11.43** x-14.17**
	P_7 x P_3 (501.03)	P7 x P3	P7 x P3	38.65** /-87.62**	17.74** x-14.17**

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