



RESEARCH ARTICLE

Heterosis and combining ability analysis for yield and yield attributing traits in bottle gourd (*Lagenaria siceraria* (Molina) Standl)

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Abstract

This study aimed to evaluate the quantitative traits of the bottle gourd (*Lagenaria siceraria* (Molina) Standl.) across different genotypes and hybrid combinations. Promising parent genotypes P_4 , P_6 and P_8 were identified based on per se performance for their quantitative traits. The top three crosses for fruit yield per plant based on high positive heterosis over the better parent were $P_1 \times P_8$ followed by $P_4 \times P_9$ and $P_1 \times P_4$ whereas the top three crosses for positive heterosis over the standard variety were $P_2 \times P_5$ followed by $P_1 \times P_8$ and $P_6 \times P_9$ for this trait. Only two parents P_5 and P_4 exhibited significant and positive general combining ability (GCA) effects for fruit yield per plant. For specific combining ability (SCA), the following hybrids excelled for individual traits, $P_1 \times P_3$ followed by $P_1 \times P_7$. Fruit circumference was $P_4 \times P_9$ followed by $P_2 \times P_8$, average fruit weight was $P_2 \times P_5$ followed by $P_2 \times P_8$, number of fruits per plant were $P_1 \times P_4$ followed by $P_4 \times P_6$ and fruit yield per plant $P_2 \times P_5$ followed by $P_1 \times P_8$. These hybrids exhibited superior performance and positive SCA effects in the pooled analysis, highlighting their promise for future breeding initiatives. The dominance of significant σ^2_{SCA} values over σ^2_{GCA} values emphasised the influence of dominant gene action in controlling these traits, indicating the effectiveness of hybrid breeding for genetic improvement.

Keywords: bottle gourd; combining ability; fruit yield; genotypes; heterosis

Introduction

Bottle gourd (*Lagenaria siceraria* (Molina) Standl.), chromosome number: $2n = 2x = 22$ is an important cucurbitaceous vegetable crop known as white-flowered gourd and Lauki. This crop exhibits a wide range of genetic variability within the cultivated varieties found across the country. The global cultivation area for pumpkins, including squash and gourds, is approximately 1.55 Mha, with a total production of 23.68 Mt (1). In India, vegetable crops alone contribute 58.83 % of total horticulture production, with a production of 197.26 Mt from 10.9 Mha of land (1). It is composed of approximately 92–96 % water, making it an excellent hydrating food with low calories, which makes it beneficial for weight management and digestion (2). It provides dietary fibre those aids in digestion, prevents constipation and promotes gut health (3). Rich in essential vitamins and minerals, bottle gourd contains vitamin C, B-complex vitamins (B_1 , B_2 , B_3) and small amounts of vitamin A, which boost immunity, support metabolism and promote eye health (4). It is also an excellent source of potassium (K), which regulates blood pressure, along with calcium (Ca), magnesium (Mg) and iron (Fe), which are essential for bone health and blood formation (5). Its high-water content and alkaline nature make it effective for detoxification,

cooling the body and preventing acidity (6). It is beneficial for diabetes management as its low glycaemic index and fibre help regulate blood sugar levels (7). Additionally, its antioxidant and anti-inflammatory properties protect against oxidative stress, improve heart health and enhance liver function (8). Due to its medicinal properties, bottle gourd is widely used in ayurveda for treating digestive disorders, ulcers and liver-related ailments (9). Regular consumption supports cardiovascular health, weight control and overall well-being, making it a valuable component of a balanced diet.

Heterosis or hybrid vigour, is a well-known phenomenon that enhances yield and other agronomic traits in crops through the exploitation of genetic diversity (10). It plays a crucial role in hybrid breeding programs by increasing vigour, earliness, fruit yield and disease resistance. In bottle gourd, heterosis has been reported for various quantitative traits, including fruit weight, fruit number and vine length, making it an essential tool for crop improvement (11).

Combining ability analysis helps in understanding the gene action governing trait inheritance and is critical for selecting suitable parents for hybrid development (12). General combining ability (GCA) refers to the additive genetic effects of a parent, whereas

specific combining ability (SCA) indicates the non-additive effects, including dominance and epistasis (13). Evaluating GCA and SCA provides insights into the genetic control of yield-contributing traits and assists in formulating efficient breeding strategies for bottle gourd improvement (14).

The present study aims to assess heterosis and combining ability for key quantitative traits in bottle gourd to identify superior hybrids and parental lines for breeding programs. By analysing genetic interactions, this research contributes to the enhancement of bottle gourd productivity and the development of commercial hybrids. Despite the growing demand for high-yielding and nutritionally superior varieties, research on heterosis and combining ability in bottle gourd remains relatively limited compared to other cucurbits, such as cucumber and pumpkin (14). A deeper understanding of heterotic patterns and genetic interactions can significantly enhance breeding efficiency and accelerate hybrid development in this crop. Additionally, identifying superior parental combinations through systematic hybridization and evaluation can contribute to sustainable agricultural practices by improving resource use efficiency and disease resistance in bottle gourd (15).

Materials and Methods

The experiment was conducted during the zaid seasons of 2023 and 2024 at the Main Experimental Station, Department of Vegetable Science, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh. The site, situated in a humid subtropical climate at 24.47°–26.56°N latitude and 82.12°–83.58°E longitude, has an altitude of 113 m above sea level. The soil is sandy-loam with moderate fertility and a pH range of 6.5–8.5. Nine genetically diverse and elite genotypes- Narendra Kamna, Narendra Rashmi, NDBG-619, NDBG-7, Narendra Pooja, Pant Lauki-3, Kashi Ganga, Arka Bahar and Pusa Naveen were selected for hybridisation based on their economic traits. A half-diallel mating design was

employed, generating 36 hybrids from all possible crosses except reciprocals. The hybrids, along with selfed parental lines, were evaluated in a randomised complete block design (RCBD) with three replications, following recommended agronomic practices. The observation was recorded in days to first staminate flower anthesis, days to first pistillate flower anthesis, node number to first staminate flower appearance, node number to first pistillate flower appearance, number of primary branches per plant, vine length, internodal length, days to first fruit harvest, fruit length, fruit circumference, average fruit weight, number of fruits per plant and fruit yield.

The pooled analysis of variance was conducted manually using MS Excel 2013, following the methodology of (16). Data from 36 crosses and their 9 parents were analysed to assess heterosis, which was evaluated concerning the better parent (BP) and standard parent (SP). The formulas for heterosis estimation were based on the methods of some previous studies (17, 18). Additionally, additive and dominance genetic variance were calculated (19).

Results and Discussion

Per se performance and heterosis results revealed significant and desirable variations in all the nutritional characteristics examined and the pooled mean value ranged between all the traits, viz. days to first staminate flower anthesis ranged from 46.75–55.42 for parents and 47.08–56.75 for hybrids (Table 1 and 2). Days to first pistillate flower anthesis ranged from 54.75–62.50 for parents and 53.92–63.75 for hybrids. Node number to first staminate flower appearance ranged from 5.62–10.39 for parents and 5.97–10.77 for hybrids. Node number to first pistillate flower appearance ranged from 12.45–16.89 for parents and 12.47–17.27 for hybrids. Number of primary branches per plant ranged from 7.48–9.24 for parents and 5–10.75 for hybrids. Vine length ranged from 3.39–6.69 for parents and 4.59–6.76 for hybrids.

Table 1. Pooled per se performance of parents, hybrids and standard check for quantitative traits

	Days to first staminate flower anthesis	Days to first pistillate flower anthesis	Node number to first staminate flower appearance	Node number to first pistillate flower appearance	Number of primary branches per plant,	Vine length	Internodal length
Range (Parents)	46.75–55.42	54.75–62.50	5.62–10.39	12.45–16.89	7.48–9.24	3.39–6.69	7.48–10.83
Mean	49.49	57.45	7.47	14.01	8.70	5.88	9.60
Parents (Best)	P ₄ , P ₅ , P ₂ , P ₆	P ₄ , P ₆ , P ₅ , P ₇	P ₅ , P ₆ , P ₇ , P ₂	P ₆ , P ₅ , P ₇ , P ₂	P ₄ , P ₆ , P ₉ , P ₁	P ₈ , P ₁ , P ₇ , P ₅	P ₁ , P ₃ , P ₆ , P ₈
Range (Hybrids)	47.08–56.75	53.92–63.75	5.97–10.77	12.47–17.27	5–10.75	5.59–6.76	9.02–11.43
Mean	50.69	58.94	8.42	14.93	8.10	6.14	10.28
Hybrid (Best)	P ₃ × P ₆ P ₁ × P ₂ P ₂ × P ₄	P ₃ × P ₆ P ₁ × P ₂ P ₂ × P ₄	P ₃ × P ₆ P ₂ × P ₄ P ₁ × P ₂	P ₃ × P ₆ P ₂ × P ₄ P ₁ × P ₂	P ₈ × P ₉ P ₁ × P ₆ P ₁ × P ₃	P ₂ × P ₃ P ₁ × P ₇ P ₄ × P ₅	P ₃ × P ₆ P ₁ × P ₂ P ₅ × P ₆
Mean (Check)	50.83	59.33	9.01	15.51	9.67	5.49	10.38
S EM±	0.54	0.60	0.28	0.48	0.27	0.19	0.33
CD (5 %)	1.07	1.19	0.56	0.96	0.54	0.38	0.66

Table 2. Pooled per se performance of parents, hybrids and standard check for quantitative traits

	Days to first fruit harvest	Fruit length	Fruit circumference	Average fruit weight	Number of fruits per plant	Fruit yield/plant (kg)
Range (Parents)	63.42–71.17	28.73–41.23	5.72–7.23	0.96–1.08	3.42–4.71	3.59–4.81
Mean	66.10	36.59	6.33	1.02	4.27	4.36
Parents (Best)	P ₄ , P ₆ , P ₅ , P ₇	P ₂ , P ₅ , P ₆ , P ₉	P ₉ , P ₅ , P ₂ , P ₃	P ₇ , P ₅ , P ₄ , P ₆	P ₂ , P ₆ , P ₅ , P ₃	P ₆ , P ₇ , P ₅ , P ₂
Range (Hybrids)	62.58–72.42	30.23–42.60	5.18–10.25	0.89–1.35	3.27–5.32	3.08–6.65
Mean	67.65	37.65	7.19	1.05	4.32	4.37
Hybrid (Best)	P ₃ × P ₆ P ₁ × P ₂ P ₂ × P ₄	P ₆ × P ₉ P ₅ × P ₈ P ₆ × P ₈	P ₄ × P ₈ P ₄ × P ₉ P ₂ × P ₈	P ₂ × P ₅ P ₂ × P ₈ P ₃ × P ₄	P ₅ × P ₈ P ₂ × P ₉ P ₄ × P ₆	P ₂ × P ₅ P ₁ × P ₈ P ₆ × P ₉
Mean (Check)	68	32.37	7.48	0.97	4.39	4.26
S EM±	0.02	1.14	0.22	0.03	0.13	0.15
CD (5 %)	4.02	2.27	0.44	0.06	0.27	0.30

Internodal length ranged from 7.48–10.83 for parents and 9.02–11.43 for hybrids. Days to first fruit harvest ranged from 63.42–71.17 for parents and 62.58–72.42 for hybrids. Fruit length ranged from 28.73–41.23 for parents and 30.23–42.60 for hybrids. Fruit circumference ranged from 5.782–7.23 for parents and 5.18–10.25 for hybrids. Average fruit weight ranged from 0.96–1.08 for parents and 0.89–1.35 for hybrids. Number of fruits per plant ranged from 3.42–4.71 for parents and 3.27–5.32 for hybrids. Fruit yield per plant ranged from 3.59–4.81 kg for parents and 3.08–6.65 kg for hybrids.

The highest-performing parents, as determined by pooled per se performance, were identified as follows: P_4 and P_5 for days to first staminate flower anthesis, P_4 and P_6 for days to first pistillate flower anthesis, P_4 and P_6 for node number to first staminate flower appearance, P_4 and P_6 for node number to first pistillate flower appearance, P_4 and P_6 for number of primary branches per plant, P_8 and P_1 for vine length, P_1 and P_3 for internodal length, P_4 and P_6 for days to first fruit harvest, P_2 and P_5 for fruit length, P_2 and P_5 for fruit circumference, P_7 and P_5 for average fruit weight, P_2 and P_6 for number of fruits per plant and Pant Lauki-3 and Kashi Ganga for fruit yield per plant.

Similarly, the top four hybrids were identified as $P_5 \times P_6$ and $P_1 \times P_2$ for days to first staminate flower anthesis, $P_3 \times P_6$ and $P_1 \times P_2$ for days to first pistillate flower anthesis, $P_3 \times P_6$ and $P_2 \times P_4$ for node number to first staminate flower appearance, $P_3 \times P_6$ and $P_2 \times P_4$ for node number to first pistillate flower appearance, $P_8 \times P_9$ and $P_1 \times P_6$ for number of primary branches per plant, $P_2 \times P_3$ and $P_1 \times P_7$ for vine length, $P_2 \times P_9$ and $P_1 \times P_5$ for internodal length, $P_3 \times P_6$ and $P_1 \times P_2$ for days to first fruit harvest, $P_6 \times P_9$ and $P_5 \times P_8$ for fruit length, $P_4 \times P_9$ and $P_4 \times P_9$ for fruit circumference, $P_2 \times P_5$ and $P_2 \times P_8$ for average fruit weight, $P_5 \times P_8$ and $P_2 \times P_9$ for number of fruits per plant and $P_2 \times P_5$ and $P_1 \times P_8$ for fruit yield per plant.

The selection of parents based solely on mean performance may not always be effective in identifying superior genotypes. Therefore, heterosis, combining ability and gene action were evaluated for all the studied traits to identify the most promising parents and hybrid combinations (20).

In the present study, the pooled mean data indicated varying degrees of heterosis for days to first staminate flower anthesis across different hybrid combinations when compared to the better parent and check Sarita (Table 3 and 4). The range of heterobeltiosis varied from -12.63 % ($P_2 \times P_8$) to 14.83 % ($P_1 \times P_3$) over better parent while, for standard heterosis it varied from -7.38 % ($P_5 \times P_6$) to 11.64 % ($P_1 \times P_9$). Among the 36 cross combinations, best five crosses based on high negative value over better parent were $P_2 \times P_8$ (-12.63 %) followed by $P_1 \times P_8$ (-11.44 %), $P_7 \times P_8$ (-11.43 %), $P_6 \times P_8$ (-9.63 %) and $P_4 \times P_8$ (-9.63 %) whereas, the best five crosses for negative heterosis over standard variety were $P_5 \times P_6$ (-7.38 %) followed by $P_1 \times P_2$ (-6.06 %), $P_2 \times P_4$ (-6.06 %), $P_3 \times P_6$ (-5.41 %) and $P_6 \times P_9$ (-5.41 %) for this trait.

Days to pistillate flower anthesis range of heterobeltiosis varied from -7.73 % ($P_2 \times P_8$) to 10.39 % ($P_7 \times P_9$) over better parent while, for standard heterosis it varied from -9.12 % ($P_3 \times P_6$) to 7.45 % ($P_7 \times P_9$). Among the 36 cross combinations, best five crosses based on high negative value over better parent were $P_2 \times P_8$ (-7.73 %) followed by $P_6 \times P_8$ (-7.47 %), $P_1 \times P_2$ (-6.15 %), $P_7 \times P_8$ (-6.13 %) and $P_5 \times P_8$ (-5.87 %) whereas, the best five crosses for negative heterosis over standard variety were $P_3 \times P_6$ (-9.12 %) followed by $P_1 \times P_2$ (-7.85 %), $P_2 \times P_4$ (-5.90 %), $P_6 \times P_9$ (-5.89 %) and $P_5 \times P_6$ (-5.33 %) for this trait.

Node number to first staminate flower appearance range of heterobeltiosis varied from -32.98 % ($P_6 \times P_9$) to 75.79 % ($P_2 \times P_5$) over better parent while, for standard heterosis it varied from -33.74 % ($P_3 \times P_6$) to 19.53 % ($P_2 \times P_5$). Among the 36 cross combinations, best five crosses based on high negative value over better parent were $P_6 \times P_9$ (-32.98 %) followed by $P_1 \times P_8$ (-27.73 %), $P_3 \times P_6$ (-27.43 %), $P_1 \times P_2$ (-25.99 %) and $P_2 \times P_8$ (-25.77 %) whereas, the best five crosses for negative heterosis over standard variety were $P_3 \times P_6$ (-33.74 %) followed by $P_2 \times P_4$ (-29.78 %), $P_1 \times P_2$ (-28.05 %), $P_6 \times P_9$ (-25.86 %) and $P_5 \times P_6$ (-23.72 %) for this trait.

Node number to first pistillate flower appearance range of heterobeltiosis varied from -19.98 % ($P_6 \times P_9$) to 36.38 % ($P_2 \times P_5$) over better parent while, for standard heterosis it varied from -19.60 % ($P_3 \times P_6$) to 11.35 % ($P_2 \times P_5$). Among the 36 cross combinations, best

Table 3. Heterosis, top performing general and specific combiner for quantitative traits in bottle gourd

	Days to first staminate flower anthesis	Days to first pistillate flower anthesis	Node number to first staminate flower appearance	Node number to first pistillate flower appearance	Number of primary branches per plant	Vine length	Internodal length
Heterobeltiosis range (%)	-12.63–14.83	-7.73–10.39	-32.98–75.79	-19.98–36.38	-45.37–19.18	-27.78–13.80	-14.15–22.88
Heterobeltiosis (No.)	13	12	17	15	19	6	12
Hybrid (Best)	$P_2 \times P_8$ $P_1 \times P_8$ $P_7 \times P_8$	$P_2 \times P_8$ $P_6 \times P_8$ $P_1 \times P_2$	$P_6 \times P_9$ $P_1 \times P_8$ $P_3 \times P_6$	$P_6 \times P_9$ $P_1 \times P_8$ $P_2 \times P_8$	$P_8 \times P_9$ $P_3 \times P_7$ $P_2 \times P_3$	$P_4 \times P_9$ $P_2 \times P_3$ $P_6 \times P_9$	$P_3 \times P_6$ $P_3 \times P_8$ $P_1 \times P_8$
Standard heterosis range (%)	-7.38–11.64	-9.12–7.45	-33.74–19.53	-19.60–11.35	-48.29–11.17	-16.34–23.13	-13.13–10.14
Standard heterosis (No.)	12	7	18	15	23	26	11
Hybrid (Best)	$P_5 \times P_6$ $P_1 \times P_2$ $P_2 \times P_4$	$P_3 \times P_6$ $P_1 \times P_2$ $P_2 \times P_4$	$P_3 \times P_6$ $P_2 \times P_4$ $P_1 \times P_2$	$P_3 \times P_6$ $P_2 \times P_4$ $P_1 \times P_2$	$P_8 \times P_9$ $P_1 \times P_6$	$P_2 \times P_3$ $P_1 \times P_7$ $P_4 \times P_5$	$P_3 \times P_6$ $P_3 \times P_5$ $P_3 \times P_9$
GCA effects parents (No.)	3	3	3	3	3	5	4
Parents (Best)	P_7, P_8, P_9	P_7, P_8, P_9	P_3, P_8, P_9	P_3, P_8, P_9	P_1, P_6, P_9	P_1, P_2, P_3, P_5, P_7	P_3, P_5, P_7, P_8
SCA effects hybrids (No.)	15	17	18	16	16	19	17
Hybrids (Best)	$P_1 \times P_5, P_1 \times P_6, P_1 \times P_9$	$P_1 \times P_4, P_1 \times P_5, P_1 \times P_6$	$P_1 \times P_3, P_1 \times P_5, P_1 \times P_6$	$P_1 \times P_2, P_1 \times P_5, P_1 \times P_9$	$P_1 \times P_3, P_1 \times P_6, P_1 \times P_7$	$P_1 \times P_3, P_1 \times P_5, P_1 \times P_7$	$P_1 \times P_4, P_1 \times P_6, P_1 \times P_8$

Table 4. Heterosis, top performing general and specific combiner for quantitative traits in bottle gourd

Days to first fruit harvest	Fruit length	Fruit circumference	Average fruit weight	Number of fruits per plant	Fruit yield/plant (kg)
-9.03–5.92	26.67–25.52	-23.24–66.67	-15.48–31.38	-28.50–22.59	-25.27–72.58
7	5	8	9	7	21
$P_7 \times P_9$	$P_1 \times P_3$	$P_4 \times P_8$	$P_2 \times P_8$	$P_1 \times P_4$	$P_1 \times P_8$
$P_4 \times P_9$	$P_3 \times P_8$	$P_4 \times P_7$	$P_2 \times P_5$	$P_5 \times P_8$	$P_4 \times P_9$
$P_3 \times P_5$	$P_4 \times P_7$	$P_2 \times P_8$	$P_3 \times P_4$	$P_4 \times P_6$	$P_1 \times P_4$
-7.97–4.42	-6.59–31.62	-30.78–36.98	-7.65–39.30	-25.44–21.12	-19.65–73.49
6	29	10	21	8	25
$P_3 \times P_6$	$P_6 \times P_9$	$P_4 \times P_8$	$P_2 \times P_5$	$P_5 \times P_8$	$P_2 \times P_5$
$P_1 \times P_2$	$P_5 \times P_8$	$P_4 \times P_9$	$P_2 \times P_8$	$P_2 \times P_9$	$P_1 \times P_8$
$P_7 \times P_9$	$P_6 \times P_8$	$P_2 \times P_8$	$P_3 \times P_4$	$P_4 \times P_6$	$P_6 \times P_9$
1	3	5	3	3	2
P_8	P_2, P_6, P_8	P_4, P_5, P_7, P_8, P_9	P_4, P_5, P_9	P_5, P_9, P_6	P_4, P_5
11	17	15	12	18	23
$P_1 \times P_5, P_1 \times P_9, P_2 \times P_5$	$P_1 \times P_3, P_1 \times P_5, P_1 \times P_6$	$P_1 \times P_2, P_1 \times P_6, P_2 \times P_7$	$P_1 \times P_3, P_1 \times P_8, P_2 \times P_4$	$P_1 \times P_3, P_1 \times P_4, P_1 \times P_7$	$P_1 \times P_3, P_1 \times P_4, P_1 \times P_5$

five crosses based on high negative value over better parent were $P_6 \times P_9$ (-19.98 %) followed by $P_1 \times P_8$ (-17.04 %), $P_2 \times P_8$ (-15.85 %), $P_2 \times P_9$ (-15.45 %) and $P_3 \times P_6$ (-15.32 %) whereas, the best five crosses for negative heterosis over standard variety were $P_3 \times P_6$ (-19.60 %) followed by $P_2 \times P_4$ (-17.30 %), $P_1 \times P_2$ (-16.29 %), $P_6 \times P_9$ (-15.04 %) and $P_5 \times P_6$ (-13.78 %) for this trait.

Number of primary branches per plant the range of heterobeltiosis varied from -45.36 % ($P_2 \times P_6$) to 19.18 % ($P_8 \times P_9$) over better parent while, for standard heterosis it varied from -48.29 % ($P_2 \times P_6$) to 11.17 % ($P_8 \times P_9$). Among the 36 cross combinations, best five crosses based on high positive value over better parent were $P_8 \times P_9$ (19.18 %) followed by $P_3 \times P_7$ (15.72 %), $P_2 \times P_3$ (13.65 %), $P_1 \times P_3$ (12.98 %) and $P_1 \times P_6$ (12.57 %) whereas, the best two crosses for positive heterosis over standard variety were $P_8 \times P_9$ (11.17 %) and $P_1 \times P_6$ (6.51 %) for this trait.

Vine length (m) range of heterobeltiosis varied from -27.78 % ($P_6 \times P_7$) to 13.80 % ($P_4 \times P_9$) over better parent while, for standard heterosis it varied from -16.34 % ($P_6 \times P_7$) to 23.13 % ($P_2 \times P_3$). Among the 36 cross combinations, best five crosses based on high positive value over better parent were $P_4 \times P_9$ (13.80 %) followed by $P_2 \times P_3$ (9.80 %), $P_6 \times P_9$ (9.15 %), $P_2 \times P_9$ (9.10 %) and $P_2 \times P_4$ (7.49 %) whereas, the best five crosses for positive heterosis over standard variety were $P_2 \times P_3$ (23.13 %) followed by $P_1 \times P_7$ (22.22 %), $P_4 \times P_5$ (21.31 %), $P_1 \times P_3$ (20.95 %) and $P_2 \times P_5$ (20.95 %) for this trait.

Internodal length (cm) range of heterobeltiosis varied from -14.15 % ($P_1 \times P_7$) to 22.68 % ($P_3 \times P_6$) over better parent while, for standard heterosis it varied from -13.13 % ($P_2 \times P_9$) to 10.14 % ($P_3 \times P_6$). Among the 36 cross combinations, best five crosses based on high positive value over better parent were $P_3 \times P_6$ (22.68 %) followed by $P_3 \times P_8$ (20.57 %), $P_1 \times P_8$ (20.00 %), $P_4 \times P_6$ (13.07 %) and $P_4 \times P_5$ (11.27 %) whereas, the best five crosses for positive heterosis over standard variety were $P_3 \times P_6$ (10.14 %) followed by $P_3 \times P_5$ (9.34 %), $P_3 \times P_9$ (9.34 %), $P_4 \times P_5$ (9.34 %) and $P_5 \times P_8$ (9.25 %) for this trait.

Days to first fruit harvest range of heterobeltiosis varied from -9.03 % ($P_7 \times P_9$) to 5.92 % ($P_2 \times P_7$) over better parent while, for standard heterosis it varied from -7.97 % ($P_3 \times P_6$) to 4.42 % ($P_3 \times P_5$). Among the 36 cross combinations, best five crosses based on high negative value over better parent were $P_7 \times P_9$ (-9.03 %) followed by $P_4 \times P_9$ (-8.40 %), $P_3 \times P_5$ (-7.99 %), $P_1 \times P_9$ (-7.22 %) and $P_4 \times P_5$ (-6.95 %) whereas, the best five crosses for negative heterosis over standard variety were $P_3 \times P_6$ (-7.97 %), $P_1 \times P_2$ (-6.86 %), $P_7 \times P_9$ (-6.50 %), $P_4 \times P_9$ (-5.88 %) and $P_1 \times P_9$ (-5.51 %) for this trait.

Fruit length (cm) range of heterobeltiosis varied from -26.67 % ($P_1 \times P_2$) to 25.52 % ($P_1 \times P_3$) over better parent while, for standard heterosis it varied from -6.59 % ($P_1 \times P_2$) to 31.62 % ($P_6 \times P_9$). Among the 36 cross combinations, best five crosses based on high positive value over better parent were $P_1 \times P_3$ (25.52 %) followed by $P_3 \times P_8$ (23.03 %), $P_4 \times P_7$ (8.94 %), $P_1 \times P_7$ (8.75 %) and $P_1 \times P_8$ (7.84 %) whereas, the best five crosses for positive heterosis over standard variety were $P_6 \times P_9$ (31.62 %) followed by $P_5 \times P_8$ (31.20 %), $P_6 \times P_8$ (29.35 %), $P_2 \times P_5$ (28.73 %) and $P_1 \times P_3$ (28.62 %) for this trait.

Fruit circumference the range of heterobeltiosis varied from -23.24 % ($P_3 \times P_9$) to 66.67 % ($P_4 \times P_8$) over better parent while, for standard heterosis it varied from -30.78 % ($P_1 \times P_3$) to 36.58 % ($P_4 \times P_8$). Among the 36 cross combinations, best five crosses based on high positive value over better parent were $P_4 \times P_8$ (66.67 %) followed by $P_4 \times P_7$ (51.09 %), $P_2 \times P_8$ (46.29 %), $P_5 \times P_8$ (40.69 %) and $P_4 \times P_9$ (39.93 %) whereas, the best five crosses for positive heterosis over standard variety were $P_4 \times P_8$ (36.98 %) followed by $P_4 \times P_9$ (35.20 %), $P_2 \times P_8$ (31.63 %), $P_5 \times P_8$ (27.22 %) and $P_4 \times P_7$ (23.17 %) for this trait.

Average fruit weight (kg) range of heterobeltiosis varied from -15.48 % ($P_7 \times P_8$) to 31.38 % ($P_2 \times P_8$) over better parent while, for standard heterosis it varied from -7.65 % ($P_6 \times P_8$) to 39.30 % ($P_2 \times P_5$). Among the 36 cross combinations, best five crosses based on high positive value over better parent were $P_2 \times P_8$ (31.38 %) followed by $P_2 \times P_5$ (27.04 %), $P_3 \times P_4$ (16.24 %), $P_1 \times P_8$ (15.09 %) and $P_7 \times P_9$ (9.60 %) whereas, the best five crosses for positive heterosis over standard variety were $P_2 \times P_5$ (39.30 %) followed by $P_2 \times P_8$ (31.33 %), $P_3 \times P_4$ (25.85 %), $P_1 \times P_8$ (22.03 %) and $P_7 \times P_9$ (22.03 %) for this trait.

Number of fruits per plant the range of heterobeltiosis varied from -28.50 % ($P_2 \times P_7$) to 22.59 % ($P_1 \times P_4$) over better parent while, for standard heterosis it varied from -25.44 % ($P_3 \times P_5$) to 21.12 % ($P_5 \times P_8$). Among the 36 cross combinations, best five crosses based on high positive value over better parent were $P_1 \times P_4$ (22.59 %) followed by $P_5 \times P_8$ (19.57 %), $P_4 \times P_6$ (15.49 %), $P_1 \times P_8$ (13.18 %) and $P_3 \times P_7$ (12.84 %) whereas, the best five crosses for positive heterosis over standard variety were $P_5 \times P_8$ (21.12 %) followed by $P_2 \times P_9$ (20.96 %), $P_4 \times P_6$ (20.57 %), $P_1 \times P_4$ (18.68 %) and $P_6 \times P_9$ (15.79 %) for this trait.

The range of heterobeltiosis for fruit yield per plant varied from -25.37 % ($P_2 \times P_7$) to 72.58 % ($P_1 \times P_8$) over the better parent, while for standard heterosis, it varied from -19.65 % ($P_1 \times P_6$) to 73.49 % ($P_2 \times P_5$). Among the 36 cross combinations, the top three crosses based on high positive heterosis over the better parent were

$P_1 \times P_8$ (72.58 %), followed by $P_4 \times P_9$ (62.47 %) and $P_1 \times P_4$ (61.39 %), whereas the top three crosses for positive heterosis over the standard variety were $P_2 \times P_5$ (73.49 %), followed by $P_1 \times P_8$ (48.89 %) and $P_6 \times P_9$ (46.80 %) for this trait. Similar findings have been reported previously, where heterosis for fruit yield per vine ranged from -35.2–23.9 % over the mid-parent and from -17.6–68.5 % over the standard check variety 'Samrat'. Notably, the hybrid 'Samrat $\times$ Aditi' exhibited 68.5 % standard heterosis, highlighting the considerable potential of heterosis for yield improvement in bottle gourd (21). Significant heterosis has also been reported for nutritional quality traits, with the hybrid $P_2 \times P_7$ showing superiority for dry matter content, ascorbic acid and total soluble solids. These findings demonstrate the potential of heterosis to improve both yield and nutritional quality in bottle gourd (22).

Combining ability

Combining ability analysis is an effective method for selecting optimal parents for hybridisation, whether to enhance heterosis or to accumulate favourable genes (23). In this study, all parents demonstrated strong general combining ability (GCA) for various quality traits across both individual years and in the pooled analysis.

The combining ability analysis conducted over pooled environments revealed significant variation among genotypes for all the studied traits. General combining ability (GCA) effects were significant for all traits, indicating the importance of additive gene action. Likewise, specific combining ability (SCA) effects were significant for most traits, suggesting the involvement of non-additive gene action in the inheritance of these characters. The estimates of GCA and SCA effects for different traits are presented in Table 3 and 4.

A low GCA value (whether positive or negative) suggests little variation between parental and hybrid means. In contrast, high GCA values indicate that parental means are either notably superior or inferior compared to the overall hybrid mean. This pattern reflects the inheritance of genetic traits from parents to their progeny (24).

The SCA effects in negative direction were considered desirable for maturity traits viz., days to first staminate and pistillate flower anthesis, node number to first staminate flower appearance, days to first fruit harvest and internodal length. Similarly, the best hybrids for days to first staminate flower anthesis were $P_7 \times P_8$ and $P_1 \times P_8$ in over seasons (pooled), for days to first pistillate flower anthesis were $P_1 \times P_2$ and $P_3 \times P_6$, node number to first staminate flower appearance were $P_1 \times P_8$ and $P_3 \times P_6$, node number to first pistillate flower appearance were $P_1 \times P_2$ followed by $P_3 \times P_6$, primary branches

per plant were $P_2 \times P_3$ followed by $P_8 \times P_9$, vine length were $P_4 \times P_5$ followed by $P_4 \times P_7$, internodal length were $P_1 \times P_8$ followed by $P_2 \times P_6$, days to first fruit harvest were $P_1 \times P_2$ (-3.73) followed by $P_3 \times P_6$, fruit length were $P_1 \times P_3$ followed by $P_1 \times P_7$, fruit circumference were $P_4 \times P_9$ followed by $P_2 \times P_8$, average fruit weight were $P_2 \times P_5$ (0.27) followed by $P_2 \times P_8$, number of fruits per plant were $P_1 \times P_4$ followed by $P_4 \times P_6$ and fruit yield per plant $P_2 \times P_5$ followed by $P_1 \times P_8$. These hybrids exhibited superior performance and positive SCA effects in the pooled analysis, highlighting their promise for future breeding initiatives.

Strong SCA effects, particularly when paired with high-GCA parents, indicate the potential for developing valuable transgressive segregants in future generations (25). Interestingly, the findings reveal that superior hybrids can emerge even from parents with low GCA, emphasising that high GCA combinations are not the sole determinants of successful crosses (Table 3 and 4). Crosses influenced by additive gene action, which is heritable and fixable, show great promise for heterosis breeding and segregant selection in later generations. Similar observations have been reported in studies by (26, 27).

Genetic component of variance

In bottle gourd (*L. siceraria*) the genetic components of variance, namely general combining ability variance (σ^2 GCA), specific combining ability variance (σ^2 SCA), additive genetic variance (σ^2 A), dominance genetic variance (σ^2 D) and the ratio of σ^2 GCA- σ^2 SCA, are critical for understanding inheritance patterns and formulating effective breeding strategies (Table 5). These studies collectively indicate that although both additive and non-additive genetic variances contribute to trait inheritance, non-additive effects often play a more prominent role. Consequently, breeding approaches that exploit heterosis, such as hybrid development, may be particularly effective for enhancing yield and other desirable traits in bottle gourd. Similar findings have been reported in earlier studies. A line $\times$ tester analysis involving 12 genotypes and their 27 hybrids revealed that σ^2 SCA was higher than σ^2 GCA for all studied traits, indicating the predominance of non-additive gene action. Furthermore, dominance genetic variance (σ^2 D) exceeded additive genetic variance (σ^2 A), supporting the importance of dominance and over-dominance effects in trait inheritance (28). Likewise, the evaluation of 12 parents and 35 lines $\times$ tester crosses showed that the σ^2 GCA/ σ^2 SCA ratio was less than unity for all characters, suggesting a greater role of non-additive genetic variance and highlighting the effectiveness of hybrid breeding strategies for bottle gourd improvement (29, 30).

Table 5. Estimation of genetic component of variance for quantitative traits in bottle gourd

Traits	σ^2 GCA	σ^2 SCA	σ^2 A	σ^2 D	σ^2 GCA / σ^2 SCA
Days to first staminate flower anthesis	4.93	6.18	0.43	6.03	0.07
Days to first pistillate flower anthesis	6.64	4.97	0.59	4.79	0.12
Node number to first staminate flower appearance	3.15	1.91	0.28	1.87	0.15
Node number to first pistillate flower appearance	3.15	1.89	0.28	1.78	0.15
Number of primary branches per plant,	1.28	2.22	0.11	2.18	0.05
Vine length	0.60	0.35	0.05	0.33	0.16
Internodal length	1.25	0.67	0.11	0.61	0.18
Days to first fruit harvest	7.06	5.16	0.46	3.14	0.15
Fruit length	15.87	12.22	1.38	11.56	0.12
Fruit circumference	3.99	1.42	0.36	1.40	0.26
Average fruit weight	0.005	0.010	0.000	0.009	0.043
Number of fruits per plant	0.076	0.358	0.006	0.349	0.017
Fruit yield/plant (kg)	0.233	0.904	0.020	0.893	0.23

Conclusion

This study underscores the significance of heterosis and combining ability in bottle gourd breeding, identifying promising parental genotypes and superior hybrids for yield improvement. The research revealed that non-additive genetic variance plays a dominant role in trait inheritance, reinforcing the effectiveness of hybrid breeding strategies. High heterotic responses observed in specific hybrids, particularly $P_1 \times P_8$, $P_4 \times P_9$ and $P_2 \times P_5$ for fruit yield per plant, highlight their potential for commercial cultivation. Additionally, the study demonstrated that strong specific combining ability (SCA) effects are not exclusively dependent on high general combining ability (GCA) parents, emphasising the importance of strategic hybrid selection.

The findings contribute valuable insights into the genetic improvement of bottle gourd, offering a foundation for future breeding programs aimed at enhancing productivity and nutritional quality. By leveraging heterosis and specific gene interactions, breeders can optimise hybrid development, ensuring sustainable agricultural practices and increased yield potential. Continued research focusing on molecular markers and advanced breeding techniques will further refine the selection of superior genotypes, accelerating progress in bottle gourd improvement.

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Authors' contributions

VK conducted the experiment, recorded observations, analysed the data and prepared the initial draft of the manuscript. AK supervised the research work, conceptualised the study and provided critical guidance during the experimentation and manuscript preparation. DKR contributed to the experimental design and provided technical guidance during the research work. LP assisted in data collection and compilation of experimental observations. SL contributed to data interpretation and review of the manuscript. PK provided technical inputs and assisted in the analysis of results. V contributed to field experimentation and data management. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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