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Estimation of hybrid vigour and gene action for earliness and yield attributes in bitter gourd (*Momordica charantia* L.)

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Abstract

Bitter gourd cultivation in the mid-hill regions of Himachal Pradesh is constrained by low productivity and limited availability of high-performing hybrids. Therefore, the development of early, high-yielding hybrids is essential for enhancing crop performance and commercial viability. The current study was conducted during the summer-to-rainy season (March–September) 2025 at Eternal University, Himachal Pradesh, to identify superior hybrids over the standard check (Solan Hara). Twenty-one F_1 hybrids were developed from seven parental inbred lines using half-diallel mating design and evaluated in a randomised complete block design (RCBD) with 3 replications. Considerable heterotic potential was observed for flowering, growth, fruit and yield-related traits. Among the hybrids, PK-3 × PK-2 recorded the highest standard heterosis for fruit yield/vine (102.71 %), followed by P-14 × PK-3, PK-3 × PK-1 and P-14 × LBG-5. The cross P-14 × LBG-5 emerged as the most promising specific combination, exhibiting desirable specific combining ability (SCA) effects for earliness, lower nodal position of flowering, fruit attributes and yield components, while PK-3 × PK-2 and LBG-5 × LBG-5 were also promising combinations. General combining ability (GCA) analysis identified P-14 and PK-3 as superior combiners for earliness, fruit attributes and yield-related traits. Heterosis breeding would be an effective strategy for yield enhancement in bitter gourd, as these traits are largely governed by non-additive genetic effects. Specifically, parents P-14 and PK-3, along with the cross P-14 × LBG-5 and PK-3 × PK-2, emerged as promising genetic resources for breeding programs aimed at developing early, high-yielding and commercially viable hybrids. These findings provide a strong foundation for future improvements to bitter gourd across diverse agro-climatic conditions.

Keywords: combining ability; earliness; gene action; heterosis; hybrids; yield

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Introduction

Momordica charantia L., commonly referred to as bitter gourd, bitter melon, balsam pear or bitter cucumber, is an economically important cucurbitaceous vegetable belonging to the family *Cucurbitaceae.* It is a diploid species (2n = 2x = 22) believed to have originated in the Indo-Burma region, from which it spread to several tropical and subtropical regions worldwide (1). In India, bitter gourd is cultivated over an area of about 144.58 thousand hectares, with an annual output of about 1930.64 thousand MT, the major producing states being Madhya Pradesh, Gujarat, Tamil Nadu, Chhattisgarh, Odisha and Uttar Pradesh (2). The crop exhibits considerable genetic variability for morphological and reproductive traits such as floral biology, growth habit, maturity period and fruit characteristics including size, shape, colour and surface texture (3).

Bitter gourd is an important vegetable crop not only for its agronomic importance but also for its high nutritional content (including vitamins A and C) and its medicinal properties attributed to bioactive compounds such as flavonoids, antioxidants, dietary fibre and essential minerals. Despite its economic

and therapeutic significance, systematic genetic improvement programs in bitter gourd remain relatively underexplored. Being a highly cross-pollinated crop, it maintains high heterozygosity, which provides ample scope for exploitation of heterosis. Heterosis has been widely recognised as an effective breeding approach for improving yield, earliness and fruit quality in cross-pollinated crops (4).

A comprehensive understanding of the genetic control of yield and its component traits is essential for developing superior hybrids. The analysis of combining ability, a crucial genetic tool, helps in identifying superior parents and cross combinations. It partitions genetic variance into general combining ability (GCA), governed by additive genetic effects and specific combining ability (SCA), mainly influenced by non-additive gene effects (dominance and epistasis) (5). Since yield and its contributing traits are often governed by non-additive gene action and exhibit low narrow sense heritability, heterosis breeding becomes particularly effective for their improvement (6). Therefore, the present study was conducted to evaluate the genetic effects of heterosis and combining ability governing yield and yield-attributing traits in bitter gourd using a half-diallel mating design. The study aims to identify superior parental line and hybrid combination to develop early, high-yielding, high-quality cultivars suitable for diverse environments, thereby contributing to sustainable agriculture and improved nutritional security.

Materials and Methods

The experiment was conducted during the 2025 growing season (March–September) at the Experimental Research Station, Chhapang, Department of Horticulture, Eternal University, Baru Sahib, Sirmaur, Himachal Pradesh. The site is located at 30°44′20′ N latitude and 77°18′53′ N longitude, at an elevation of 912 m above mean sea level. The crop was grown under an average relative humidity of 71.39 %, high and low temperatures of 31.15 °C and 18.36 °C, respectively and an average annual rainfall of 620.4 mm. The study comprised 21 F_1 hybrids produced by crossing seven distinct and promising inbred lines using a half-diallel mating design with a standard check (Solan Hara). The seven parental genotypes utilised in the present investigation, along with their respective accession numbers, are presented in Table 1.

Hand emasculation and pollination were performed on selected pistillate flowers. Flower buds expected to open the next day were bagged in the evening to prevent unwanted pollination. The following morning (6:00–8:00 AM), pollen from bagged staminate flowers was manually transferred to the stigma of pistillate flowers. After pollination, flowers were re-bagged and labelled. Bags were removed after 3-5 days. Using this method, 21 cross combinations were produced. Seeds from mature fruits were extracted, dried and stored with proper labels.

Statistical analysis

The 21 resulting hybrids, along with their parental lines and a standard check, were evaluated from March to September 2025 under field conditions. Seeds were sown in pro-trays on 18th March, 2025 and healthy, uniform seedlings were transplanted to the experimental field on 8th April, 2025. The experiment was laid out in a randomised complete block design (RCBD) with three replications. Each genotype was planted in a single row of 8 plants, with 90 cm between rows and 60 cm between plants. The experimental field was thoroughly prepared by ploughing and harrowing to obtain a fine tilth, followed by proper layout of the lines. The crop was raised in accordance with the recommended agronomic practices for bitter gourd. Well-decomposed organic matter and the recommended dose of nitrogen, phosphorus and potassium (NPK) fertilisers were applied, with N supplied in split doses. Irrigation was provided immediately after transplanting and subsequently at appropriate intervals based on crop requirements and prevailing weather conditions. Weeding, hoeing, staking/trellising and other intercultural operations were carried out uniformly. Major insect pests (red pumpkin beetle, aphids and whiteflies) and diseases (powdery mildew, downy mildew, fusarium wilt and mosaic) were managed through need-based application of recommended plant protection measures.

Data were recorded from five randomly selected vines per replication for various earliness, growth and yield-attributing traits. Days to first male and female flower were recorded as the number of days from transplanting to the opening of the first staminate and pistillate flower, respectively. The nodes bearing first staminate and pistillate flowers were recorded by counting the nodal position from the base of the vine. Vine length (cm) was measured from the base to the growing tip of the main vine. Fruit length (cm) and diameter (cm) were measured from representative marketable fruits with a vernier calliper, while fruit weight (g) was determined using an electronic weighing balance. Number of fruits/vine was recorded by counting the total number of fruits harvested from each selected vine over the entire harvesting period. Fruit yield/vine (kg) was determined by recording the fruit weight at each successive picking and summing the weights of all harvests from the end of May to 20 September, 2025. Heterosis was assessed as the percentage increase or decrease in mean F_1 performance relative to mid-parent, better-parent and standard check (7). Combining ability variance and effects were calculated according to Griffing (5), using diallel analysis.

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Table 1. List of parental lines with check varieties along with their sources

Sl. No.	Parents / Commercial checks	Notation	Source	Salient features
1	Punjab-14	P-14	PAU, Ludhiana	Early maturing, Fruits medium-long, oblong, green with prominent tubercles, relatively tolerant to pest and diseases, good in nutritive value. Grown successfully in both summer and rainy seasons.
2	Local Bitter Gourd-6	LBG-6	Eternal University, Baru Sahib	Strong plant vigor, light-green fruits, moderate but rather thick spines, broad to elliptical fruits, good shelf life, suitable for long-distance transportation also
3	Local Bitter Gourd-5	LBG-5	Eternal University, Baru Sahib	Produces medium-green, broad oblong fruits with obtuse end, prominent longitudinal ridges and a distinctly tuberculate, ideal for fresh market, early high-quality
4	Local Bitter Gourd-4	LBG-4	Eternal University, Baru Sahib	Dark green, medium fruit with smooth skinned, vigorous vines, intermediate tolerance to diseases and uniform fruiting
5	Pant Karela-3	PK-3	GBPUA&T, Pantnagar, Uttarakhand,	Produces attractive, long, green fruits with tubercles and spiny surface generally long than other varieties
6	Pant Karela-2	PK-2	GBPUA&T, Pantnagar, Uttarakhand	Attractive dark green with tapering end or glossy green medium-long fruits with thin, tolerance to downy mildew, powdery mildew and mosaic viruses.
7	Pant Karela-1	PK-1	GBPUA&T, Pantnagar, Uttarakhand	Early maturing, high yielding, distinctive warty and spiny surface, suitable for North India
8	Solan Hara	SH	Dr. YSPUH&F, Nauni, Solan	Light-green, tubercled fruits, suitable for low and mid hill conditions, good keeping quality and a relatively long shelf life

a) Estimation of GCA effects

$$g_i=\frac{1}{P+2}\left[\sum\left(Y_i+Y_{ii}\right)-\frac{2}{P}\right]Y..$$

b) Estimation of SCA effects

$$g_i=\frac{1}{P+2}\left[\sum\left(Y_i+Y_{ii}\right)-\frac{2}{(P+1)(P+2)}\right]Y..$$

Where,

Y_j= total of the array involving the jth parent

The relative magnitude of GCA and SCA was used to infer the nature of gene action; a high GCA : SCA ratio indicated the predominance of additive gene action, whereas a low ratio suggested non-additive gene effects. The results of heterosis, combining ability variance and the magnitude of its genetic nature were statistically analysed using WinDostat version 9.2 Software.

Results

Estimation of heterosis (Mid parent (MP), better parent (BP) and standard heterosis (SH))

Analysis of variance (ANOVA) for genotypes was performed prior to heterosis estimation to assess the significance of differences among genotypes across all studied traits. The mean sum of squares due to parental lines differed significantly across all traits (Table 2). Data about heterosis for yield and related traits indicate ample genetic variability and the feasibility of improving economic characters through hybridisation and heterosis breeding in bitter gourd.

The estimate of relative heterosis, heterobeltiosis and commercial check for days to opening of first male flower (Fig. 1). LBG-6 × PK-3 (-7.18 %, -16.74 %) exhibited the highest significant negative heterosis over the MP and BP, respectively, while P-14 × PK-3 (-14.70 %), followed by PK-3 × PK-2 (-12.46 %), P-14 × LBG-5 (-11.54 %) and PK-2 × PK-1 (-11.10 %) exhibited the highest negative heterosis over the SH. Among 21 F_1 hybrids, 13, 18 and 13 hybrids exhibited significant desirable negative heterosis (MP, BP and SH), respectively. The cross PK-3 × PK-2 (-23.78 %) exhibited the highest significant negative heterosis over the MP, while LBG-6 × PK-3 (29.64) recorded the highest significant negative heterosis over the BP. The cross P-14 × PK-3 (24.21 %), followed by PK-3 × PK-2 (-23.13 %), P-14 × LBG-5 (-22.28 %) and PK-2 × PK-1(-21.45 %) exhibited the highest significant negative heterosis over the SH. Among the 21 F_1 hybrids, 19, 21 and 11 hybrids exhibited significant desirable negative heterosis over MP, BP and SH, respectively, for days to first female flowering (Fig. 1).

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Table 2. Analysis of variance for different earliness and yield traits in bitter gourd

SOV	df	Days to opening of first male flower	Days to opening of first female flower	Nodes bearing first staminate flower	Nodes bearing first pistillate flower	Vine length	Fruit length	Fruit diameter	Fruit weight	Number of fruits/vine	Fruit yield/vine
Replication	2	240.66**	503.04**	104.95**	31.48**	64125.50**	90.39**	1.47**	380.05**	643.23**	6.19**
Genotypes	28	17.99**	49.82**	25.71**	28.05**	1727.61**	33.08**	1.75**	281.41**	122.31**	1.35**
Parents	6	22.53**	36.99**	14.02**	14.43**	1502.04**	30.54**	0.61**	202.28**	36.08*	0.53**
Hybrid	20	18.25**	21.19**	2.4525	5.33**	225.95**	13.87**	2.07**	280.56	31.32**	0.73**
Parent vs Hybrid	1	1.57**	720.92**	506.66**	553.73**	30448.89**	455.85**	2.57**	627.45**	2538.79**	18.57**
Check vs Hybrid	1	2.16**	66.34**	127.54**	75.33**	7140.65**	29.06**	1.82**	539.18**	141.37**	2.51
Error	56	0.0838	8.8902	1.10	1.16	87.21	3.95	0.15	52.60	11.82	0.15

SOV: source of variation; df: degrees of freedom. * Significant at $p \leq 0.05$; ** significant at $p \leq 0.01$.

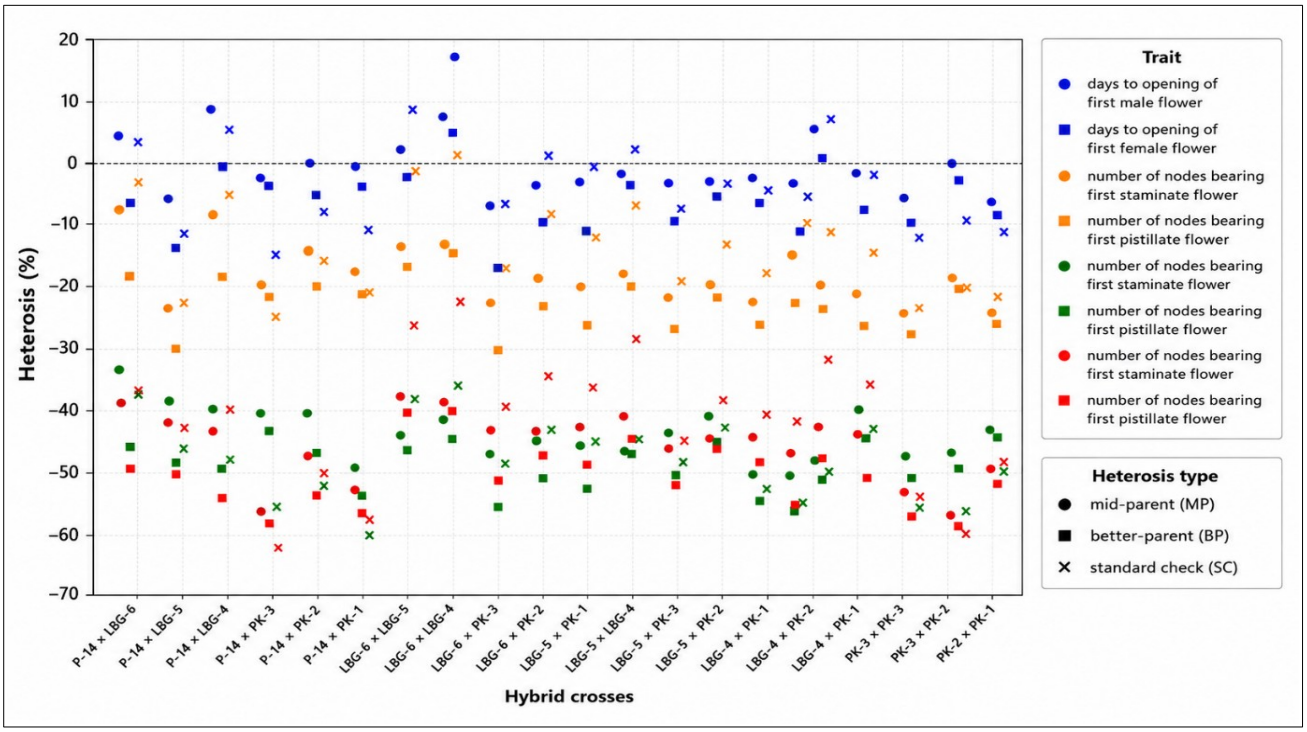

Fig. 1. Magnitude and direction of mid-parent (MP), better-parent (BP) and standard check (SC) for flowering and nodal traits in 21 F_1 hybrids of bitter gourd. Negative heterosis indicates earliness and lower node number, whereas positive heterosis indicates delayed flowering or increased node number.

All the 21 F_1 hybrids exhibited highly significant and desirable negative heterosis over the MP, BP and SH for number of nodes bearing to first staminate flower (Fig. 1). The cross LBG-4 × PK-3 exhibited the highest significant negative heterosis over the MP (-50.16 %) and BP (-55.87 %), whereas P-14 × PK-1 (-59.74 %), followed by PK-3 × PK-1 (-55.87 %), PK-3 × PK-2 (-55.39 %) and P-14 × PK-3 (-55.20 %) recorded the highest significant negative heterosis over the standard heterosis. The desirable negative and significant heterosis was shown (Fig. 1) for the number of nodes bearing the first pistillate flower, as all hybrids exhibited highly significant and desirable negative heterosis for mid, better and standard, respectively. Among the hybrids, PK-3 × PK-1 exhibited the highest significant negative heterosis over the MP (-56.47 %) and BP (-58.26), while P-14 × PK-3 (-62.10 %), followed by PK-3 × PK-1 (-59.27 %), P-14 × PK-1 (-57.26 %) and PK-3 × PK-2 (-53.63 %) recorded the highest significant negative heterosis over the standard heterosis.

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For vine length (Fig. 2), LBG-5 × LBG-4 exhibited the highest significant positive heterosis (14.50 %), followed by P-14 × LBG-5 (14.37 %) over the mid-parent. The highest significant positive heterosis was recorded by LBG-6 × LBG-4 (13.21 %), followed by LBG-5 × LBG-4 (13.02 %) over the better parent. For standard heterosis, PK-3 × PK-2 exhibited the highest significant positive heterosis (15.85 %), followed by P-14 × LBG-5 (15.26 %), P-14 × PK-2 (14.53 %) and P-14 × PK-3 (14.52 %). Among the 21 hybrids, all exhibited significant positive heterosis over MP and SH, while 19 hybrids exhibited significant positive heterosis over BP for vine length, confirming the yield significance of vine vigour.

The cross LBG-6 × LBG-4 recorded the highest significant positive relative heterosis (64.03 %), followed by LBG-5 × LBG-4 (62.52 %). The highest significant positive heterobeltiosis was recorded by LBG-5 × LBG-4 (52.23), followed by LBG-6 × LBG-4 (44.79 %). For standard heterosis, PK-3 × PK-1 exhibited the highest significant positive heterosis (35.20 %), followed by PK-2 × PK-1 (33.65 %), P-14 × PK-2 (31.72 %) and P-14 × PK-3 (31.38 %). Among the 21 F_1 hybrids, 20, 14 and 14 hybrids exhibited significant positive heterosis over the MP, BP and SH, respectively, for fruit length (Fig. 2). The cross LBG-5 × PK-2 exhibited the highest significant positive relative heterosis (36.45 %), followed by LBG-5 × PK-3 (32.65 %). The most significant positive heterobeltiosis was observed in P-14 × LBG-6 (28.00 %), followed by P-14 × LBG-5 (23.75 %). The highest significant positive standard heterosis was recorded by P-14 × LBG-5 (63.42 %), followed by LBG-6 × LBG-5 (62.89 %), LBG-5 × PK-3 (62.26 %) and P-14 × LBG-6 (61.01 %). Among the 21 F_1 hybrids, 8, 6 and 10 hybrids exhibited significant desirable positive heterosis over the MP, BP and SH, respectively, for fruit diameter (Fig. 2).

For fruit weight, 9, 7 and 12 hybrids exhibited significant desirable positive heterosis (Fig. 3) over the MP, BP and SH, respectively. The cross LBG-6 × LBG-4 exhibited the highest significant positive heterosis over the MP (26.26 %), followed by P-14 × LBG-5 (26.13 %). For heterobeltiosis, LBG-6 × LBG-4 recorded the highest significant positive heterosis (25.30 %), followed by LBG-6 × LBG-5 (21.52 %). Similarly, the most significant positive standard heterosis was observed in PK-3 × PK-2 (49.26 %), followed by P-14 × PK-3 (46.75 %) and P-14 × LBG-5 (44.11 %). Among the 21 F_1 hybrids, 20, and 19 hybrids exhibited significant desirable positive heterosis over the MP, BP and SH, respectively, for number of fruits/vine (Fig. 3). The cross LBG-5 × LBG-4 exhibited the highest significant positive heterosis over the mid-parent (76.17 %) and better-parent (71.52 %). For standard heterosis, PK-3 × PK-2 exhibited the highest significant value (37.21 %), followed by PK-3 × PK-1 (34.99 %), P-14 × PK-3 (32.67 %) and PK-2 × PK-1 (31.34 %).

Out of 21 hybrids, 14 and 15 exhibited significant desirable positive heterosis over the MP and BP, respectively and 20 exhibited significant desirable positive heterosis over the SC. The cross LBG-6 × LBG-4 exhibited the highest significant positive heterosis over the MP (105.33 %). For heterobeltiosis, LBG-5 × LBG-4 recorded the highest significant positive value (98.74 %). The significant positive standard heterosis was recorded by PK-3 × PK-2 (102.71 %), followed by P-14 × PK-3 (93.14 %), PK-3 × PK-1 (88.99 %) and P-14 × LBG-5 (81.77 %) for fruit yield/vine (Fig. 3).

General combining ability effects of parents

Table 3 revealed differential parental potential for growth and yield-attributing traits. Among the parents, PK-3 and P-14 exhibited significant and desirable GCA effects for most traits studied. PK-3 recorded significant negative GCA effects for days to opening of first male flower (-1.80), days to opening of first female flower (-1.45) and nodes bearing first staminate flower (-0.90), exhibiting the most desirable GCA effect, followed by P-14 and PK-1. For the number of nodes bearing the first pistillate flower, P-14 (-1.23) was the best general combiner, followed by PK-3 and PK-1, indicating its potential contribution towards earliness and flowering at lower nodes. The parent PK-3 also emerged as an important general combiner, exhibiting significant negative GCA effects for vine length (11.44), followed by P-14 and PK-1. Similarly, the parent P-14 was the best general combiner for fruit length (1.54), fruit weight (7.28) and fruit yield/ vine (0.35), followed by PK-3. But for fruit diameter, LBG-5 (0.60) recorded the highest positive GCA effect, followed by P-14.

Specific combining ability effects of hybrids

The SCA estimates revealed significant variation among hybrids for different traits (Table 4), indicating the importance of non-additive gene action. Among the crosses, P-14 × LBG-5 exhibited the most desirable SCA effect for days to opening of first male flower (-2.93), followed by LBG-4 × PK-2 and LBG-6 × LBG-4. For days to the opening of the first female flower (-2.11), the best specific combinations were LBG-6 × LBG-4 and P-14 × LBG-5.

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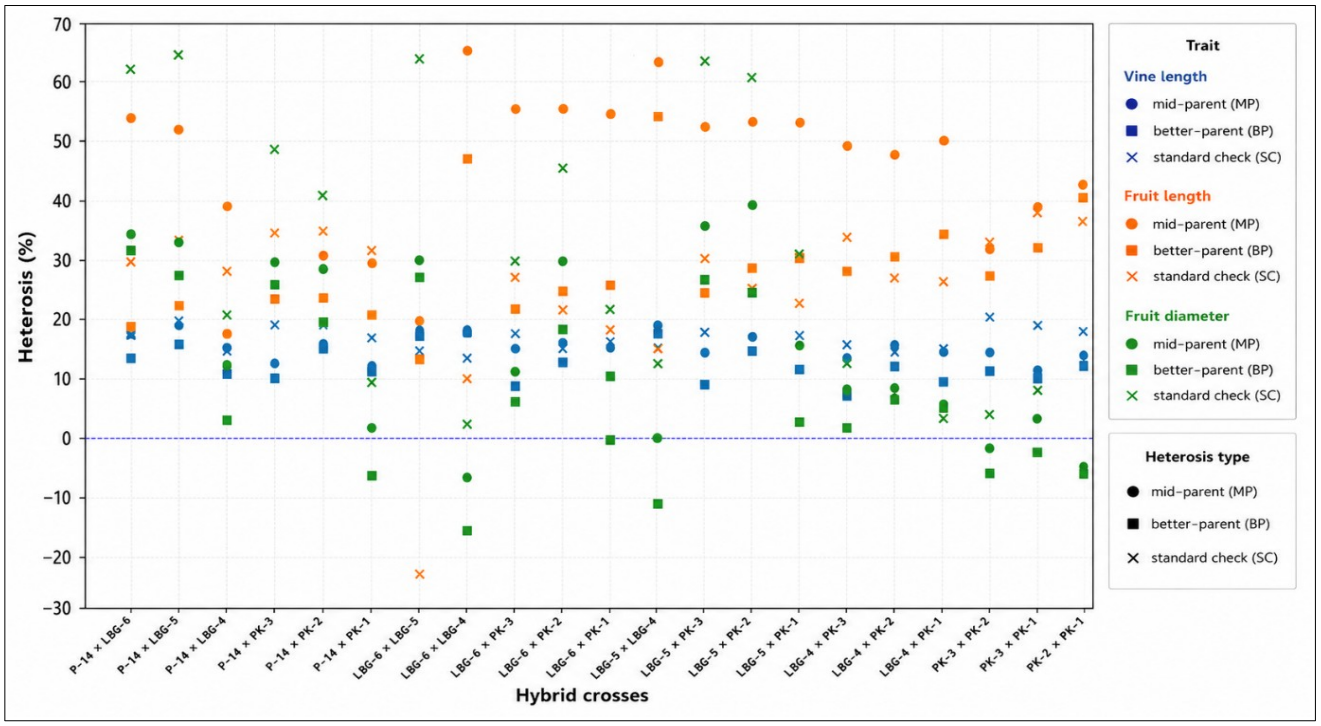

Fig. 2. Magnitude and direction of heterosis (%) over mid-parent (MP), better-parent (BP) and standard check (SC) for vine length, fruit length and fruit diameter in 21 F_1 hybrids of bitter gourd. Positive values indicate an increase in the respective traits, whereas negative values indicate a reduction relative to the corresponding parental or standard check value.

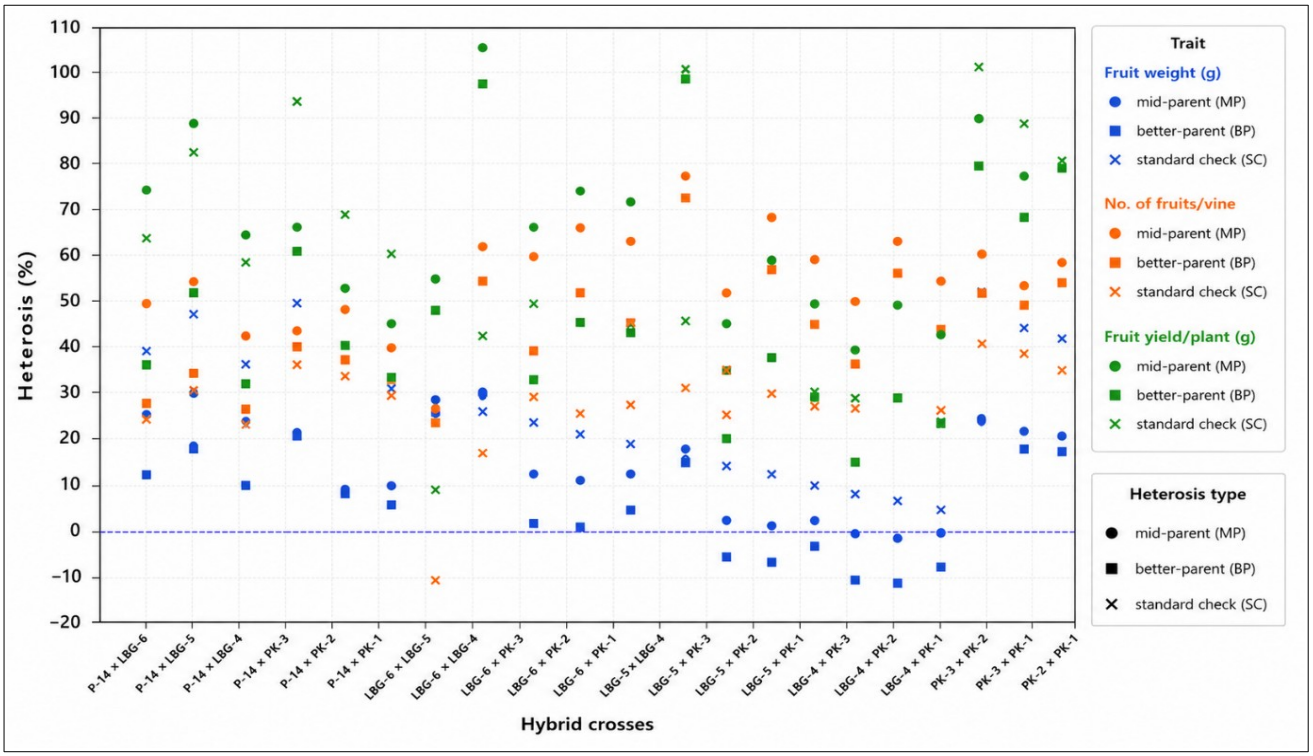

Fig. 3. Magnitude and direction of heterosis (%) over mid-parent (MP), better-parent (BP) and standard check (SC) for fruit weight, number of fruits/vine and fruit yield/vine in 21 F_1 hybrids of bitter gourd. Positive values indicate an increase in the respective trait, whereas negative values indicate a reduction relative to the corresponding parental or standard check value.

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Table 3. General combining ability (GCA) of lines for earliness and yield traits of bitter gourd

Inbred Lines	Days to opening of first male flower	Days to opening of first female flower	Nodes bearing first staminate flower	Nodes bearing first pistillate flower	Vine length	Fruit length	Fruit diameter	Fruit weight	Number of fruits/vine	Fruit yield/vine
P-14	-1.34 **	-1.45**	-0.84**	-1.23**	5.12**	1.54**	0.33**	7.28**	1.51*	0.35**
LBG-6	2.28**	2.63**	1.30**	1.22**	-8.54**	-2.23**	0.29**	-2.27	-2.78**	-0.25**
LBG-5	0.34**	0.41	0.60**	0.61**	-3.08	-1.62**	0.60**	-3.72**	-1.82**	-0.25**
LBG-4	1.967**	2.19**	0.47*	1.31**	-12.05**	-0.64	-0.55**	-6.76**	-0.88	-0.29**
PK-3	-1.8**	-1.96**	-0.90**	-1.19**	11.44**	1.45**	-0.02	3.86**	1.87**	0.26**
PK-2	-0.36**	-0.45	-0.15	-0.09	2.23	0.85*	-0.16*	1.90	1.50*	0.13*
PK-1	-1.01**	-1.37*	-0.48*	-0.65**	4.89**	0.65*	-0.50**	-0.30	1.60*	0.06

* Significance at $p \leq 0.05$; ** Significance at $p \leq 0.01$.

Table 4. Specific combining ability (SCA) of hybrids for earliness and yield of bitter gourd

F_1	Days to opening of first male flower	Days to opening of first female flower	Nodes bearing first staminate flower	Nodes bearing first pistillate flower	Vine length	Fruit length	Fruit diameter	Fruit weight	Number of fruits/ vine	Fruit yield/ vine
P-14 × LBG-6	0.95**	0.74	-0.47	-0.95	16.24**	2.70*	0.61**	4.45	3.47	0.36
P-14 × LBG-5	-1.61**	-3.73*	-0.93*	-1.03*	21.91**	2.71*	0.68**	11.01**	4.50*	0.75**
P-14 × LBG-4	1.76**	0.49	-1.06	-1.39*	8.30	0.91	0.04	7.05	1.17	0.30
P-14 × PK-3	-0.32*	-2.05	-0.70	-1.64**	4.30	-0.17	0.47*	5.03	2.62	0.44*
P-14 × PK-2	0.09	-0.48	-0.98	-1.23*	13.58**	0.49	0.34	-3.41	2.54	0.08
P-14 × PK-1	0.01	-1.35	-1.76**	-1.57**	1.62	0.15	-0.39	-2.81	1.22	-0.01
LBG-6 × LBG-5	0.92**	-0.42	-1.98**	-1.34*	13.29**	-2.69*	0.40*	8.36*	-4.17*	-0.09
LBG-6 × LBG-4	1.81**	-1.19	-1.55**	-1.64**	16.33**	1.73	-0.57**	10.11*	3.56	0.60**
LBG-6 × PK-3	-1.61**	-3.45*	-1.89**	-1.24*	11.46*	2.40*	-0.13	-2.02	4.61*	0.19
LBG-6 × PK-2	-0.90**	-2.06	-1.89**	-1.74**	9.50	2.09*	0.54*	-1.56	4.33*	0.25
LBG-6 × PK-1	-0.68**	-2.44	-1.84**	-1.43*	11.78*	1.78	0.07	-0.76	4.92**	0.29
LBG-5 × LBG-4	-0.82**	-1.97	-2.02**	-1.73**	18.81**	1.92	-0.52*	5.66	7.00**	0.66**
LBG-5 × PK-3	0.06	-2.03	-1.16*	-1.33*	7.26	2.28*	0.70**	-6.66	2.45	-0.09
LBG-5 ×PK-2	-0.22	-1.54	-1.12*	-1.63**	12.46*	2.08*	0.74**	-6.11	4.77*	0.10
LBG-5 ×PK-1	0.06	-2.22	-2.15**	-1.36*	11.35*	1.87	0.07	-5.31	3.86*	0.02
LBG-4 × PK-3	-0.93**	-0.61	-1.95**	-1.63**	6.69	1.90	0.11	-7.72*	1.92	-0.17
LBG-4 × PK-2	1.38**	-2.52*	-2.00**	-1.53**	9.83	1.38	0.07	-6.86	3.53	-0.05
LBG-4 × PK-1	-0.74**	-2.79*	-0.74	-1.47*	10.02*	1.49	0.27	-5.84	2.62	-0.07
PK-3 × PK-2	-0.64**	-2.67*	-1.41*	-1.73**	12.67*	2.27*	-0.57**	11.93**	4.45*	0.84**
PK-3 × PK-1	0.88**	-0.55	-1.16*	-1.87**	4.23	2.28*	-0.09	9.11*	3.77*	0.66**
PK-2 × PK-1	-1.11**	-2.66*	-1.03	-1.57**	9.19	2.65*	-0.42*	9.47*	3.75*	0.62**

The cross P-14 × LBG-5 also recorded the highest desirable negative SCA effects for nodes bearing the first staminate flower (-2.10) and nodes bearing the first pistillate flower (-2.41), indicating its usefulness for the development of hybrids with earlier flowering and lower nodal position of staminate and pistillate flowers.

The cross LBG-5 × LBG-4 exhibited the highest positive SCA effects for vine length (63.67) as vegetative growth, followed by P-14 × LBG-5 and PK-3 × PK-2. For fruit attributes, P-14 × LBG-5 was the best specific combination for fruit length (3.79), followed by PK-3 × PK-2 and P-14 ×LBG-6. The highest positive SCA effect for fruit diameter was

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observed in LBG-5 × LBG-4 (0.99), followed by P-14 × LBG-5 and PK-2. For fruit weight, P-14 × LBG-5 (9.03) was superior, followed by PK-3 × PK-2 and LBG-5 × LBG-4. With respect to yield components, P-14 × LBG-5 exhibited the highest positive SCA effect for number of fruits/vine (5.38) and fruit yield/vine (0.73), followed by PK-3 × PK-2 and LBG-5 × LBG-4.

Estimation of gene action

Analysis of variance demonstrated highly significant differences among parents and F_1 hybrids for all 10 traits studied (Table 5). The variance ratio of σ^2GCA/σ^2SCA was <1 for yield and related traits, suggesting the predominance of non-additive gene action. Similarly, the predictability ratio for most growth and yield traits was < 0.5, implying the greater influence of dominance and epistatic effects. This was substantiated by the greater magnitude of dominance effects (σ^2D) relative to additive variance (σ^2A) and by the σ^2A/σ^2D ratio being below unity. Although high estimates of broad-sense heritability (≥80 %) were observed, the corresponding narrow-sense heritability values were low (<50 %), suggesting limited contribution of additive effects and a greater role of dominance components.

Discussion

The present investigation revealed substantial genetic variability among the parental lines and their F_1 hybrids for earliness, growth and fruit- and yield-related traits, indicating considerable scope for genetic improvement in bitter gourd. The differential expression of heterosis and combining ability across traits reflected the diverse genetic potential of the parental combinations. The observed magnitude and direction of heterosis, together with GCA and SCA effects with genetic variance components, provide important insights into the inheritance of economically important traits and their potential exploitation through appropriate breeding strategies.

Earliness is an important breeding objective in bitter gourd, as early flowering and fruit production facilitate earlier market availability and may extend the productive period. Several hybrids exhibited desirable negative heterosis in the present investigation. For days to opening of the first male and female flowers, LBG-6 × PK-3 exhibited pronounced negative heterosis over the mid and better parent, whereas P-14 × PK-3 showed highly desirable negative standard heterosis. Such negative heterotic effects indicate the potential of these crosses to develop early flowering. The findings are consistent with earlier reports (6, 8–11), which also documented desirable negative heterosis for flowering traits in bitter gourd.

A similar trend was evident for the nodal position of the first staminate and pistillate flowers, for which desirable negative heterosis was observed. The appearance of flowers, particularly pistillate flowers, at lower nodes is considered advantageous because it facilitates earlier fruit set and, consequently, earlier harvesting. The pronounced negative heterosis observed for these characters suggests favourable interactions of parental genes governing flowering behaviour and nodal position. Therefore, crosses exhibiting early flowering and fewer pistillate flowering nodes could be valuable for breeding early-maturing hybrids. These observations are also consistent with previous studies (6, 8–12) reporting considerable heterotic potential in earliness-related characters.

Table 5. Genetic analysis of bitter gourd for earliness and yield traits

Characters	Days to opening of first male flower	Days to opening of first female flower	Nodes bearing first staminate flower	Nodes bearing first pistillate flower	Vine length	Fruit length	Fruit diameter	Fruit weight	Number of fruits/vine	Fruit yield/vine
σ^2 g Variance	2.61	2.99	0.64	1.11	65.60	2.12	0.18	20.72	2.86	0.07
σ^2 s Variance	1.23	10.23	8.04	8.47	490.90	7.38	0.21	41.71	41.16	0.35
σ^2 g/ σ^2 s Variance	2.13	0.29	0.08	0.13	0.13	0.29	0.87	0.50	0.07	0.19
Predictability ratio	0.81	0.37	0.14	0.21	0.21	0.36	0.63	0.50	0.12	0.27
σ^2 a Variance	5.21	5.97	1.27	2.23	131.19	4.24	0.37	41.44	5.72	0.13
σ^2 D Variance	1.23	10.23	8.04	8.47	490.90	7.38	0.21	41.71	41.16	0.35
h^2 Broad sense (%)	99.57	84.62	96.12	96.40	95.40	89.68	91.64	82.11	92.12	90.39
h^2 Narrow sense (%)	80.60	31.18	13.13	20.08	20.12	32.72	58.10	40.92	11.24	24.76

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Significant positive heterosis for vine length was observed across most hybrid combinations, indicating enhanced vegetative vigour in the F_1 generation. LBG-5 × LBG-4 and P-14 × LBG-5 exhibited high relative heterosis, whereas LBG-6 × LBG-4 and LBG-5 × LBG-4 showed pronounced heterobeltiosis. PK-3 × PK-2 exhibited the highest standard heterosis for this trait. Greater vine growth may contribute to the development of a larger photosynthetically active canopy, thereby improving assimilate production to support reproductive growth. However, the contribution of vigorous vine growth to productivity depends on the efficient portioning of assimilates towards developing fruits. Similar positive heterosis for vine growth has been reported in bitter gourd by earlier workers (4, 8, 10, 11).

Significant heterotic expression was also observed for fruit characteristics such as fruit length, diameter and weight, which are key determinants of fruit marketability and yield. The cross combinations, LBG-6 × LBG-4 and LBG-5 × LBG-4, showed good heterosis for fruit length and several hybrids had a significant advantage over the standard check. Heterotic combinations of plants may exhibit positive genetic interactions that affect the number and growth of fruit cells, potentially responsible for their increased length. The significant positive heterosis for fruit diameter was also noted, which was highest in LBG-5 × PK-2 and moderate in LBG-5 × PK-3, whereas highly significant positive standard heterosis was exhibited by P-14 × LBG-5. This differential fruit diameter might correlate with higher cell division, pericarp expansion and sink activity. This has been confirmed by earlier reports on heterosis in fruit size in the bitter gourd crop (4, 9, 13, 14, 16, 17). The fruit weight was also an important yield parameter, showing significant positive heterosis. The standard heterosis was high in LBG-6 × LBG-4, significantly higher than in the other crosses and mid-parent, best parent and P-14 × LBG-5, respectively. The increased fruit weight of these hybrids could have been due to favourable genetic interactions among genes affecting fruit size, assimilate production and sink strength. Superior crosses have shown promise in increasing both yield and fruit quality parameters, due to simultaneous increases in fruit weight and fruit quality. In the past, variation in fruit weight has been demonstrated in a similar fashion (10, 18, 19).

Among the yield-contributing characters, the number of fruits/vine and fruit yield/vine showed a highly significant positive association with heterosis, suggesting better reproductive efficiency of the hybrids. LBG-5 × LBG-4 had the greatest heterosis over the mid and better parent, whereas PK-3 × PK-2 recorded the highest standard heterosis. Similarly, for fruit yield per vine, LBG-6 × LBG-4 exhibited the highest relative heterosis, LBG-5 × LBG-4 showed the highest heterobeltiosis and PK-3 × PK-2 recorded the highest standard heterosis. The enhanced yield performance of these hybrids may be attributed to favourable interactions among yield-contributing characters, particularly improved fruit set, greater fruit retention, increased fruit number and higher individual fruit weight. The simultaneous expression of desirable heterosis for fruit number and fruit yield indicates the potential of these crosses for exploitation. These findings are consistent with earlier reports (6, 8, 9, 19, 20), which also demonstrated considerable heterotic potential for yield and its component traits in bitter gourd.

Combining ability analysis further revealed substantial differences in the breeding value of the parental lines. Among the parents, PK-3 and P-14 emerged as important general combiners for several economically important characters. PK-3 showed good positive GCA for days to first male flowering, days to first female flowering and nodal position of the first staminate flower, indicating that it can be utilised to improve earliness. P-14 was an important general combiner for the nodal position of the first pistillate flower, while fruit weight per fruit and fruit yield per vine had favourable general combining ability for LBG-5. The favourable GCA effects expressed by P-14 and PK-3 across multiple characters suggest the presence of useful additive genetic effects and indicate their potential as parental lines in future hybridisation programs. The same kinds of differences in parental combining ability have been previously reported by other researchers (8, 9, 13, 20 –27).

The strong SCA effects observed in the hybrid combinations suggested that certain maternal combinations were superior to those expected from their overall combining ability. P-14 × LBG-5 was an important specific cross that had good specific cross action (SCA) for early flowering in males, lower nodal position of the staminate and pistillate flowers, fruit length, fruit weight, number of fruits/vine and fruit production/vine. LBG-6 × LBG-4 indicated desirable early female flowering and LBG-5 × LBG-4 indicated desirable vine length and fruit diameter for SCA effects. The favourable specific combining ability for some fruit- and yield-related characters has also been observed in the PK-3 × PK-2 cross. The favourable dominance, combined with epistatic interactions between alleles contributed by the transmissible parents in these combinations, can explain the high SCA effects. These findings corroborate earlier studies (20, 22, 24, 26, 27) indicating that specific combining ability is important in bitter gourd improvement.

The ratio of the variance of GCA effects to the variance of the SCA effect was substantially less than unity for yield and associated characters, indicating that the non-additive effect of genes played a greater role in these characters. Similarly, the predictability ratio was low for most growth and yield characteristics, suggesting a greater role for dominance and/or epistatic effects. This was further confirmed by a higher dominance variance (σ^2D) than

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additive variance (σ^2A), with a σ^2A/σ^2D ratio <1. The high broad-sense heritability, coupled with comparatively low narrow-sense heritability, further suggested that dominance and other non-additive effects accounted for a major proportion of the genetic variation. Such genetic control suggests that improvement through direct selection may be limited, particularly in early generations, whereas exploiting heterosis through superior F_1 combinations would be more effective for these traits. A similar predominance of non-additive gene action for yield and associated characters in bitter gourd has also been reported by earlier workers (19, 26, 28, 29).

Conclusion

The present investigation demonstrated substantial scope for exploiting heterosis and combining ability for the genetic improvement of bitter gourd. Among the evaluated hybrids, PK-3 × PK-2 exhibited the highest standard heterosis for fruit yield/vine (102.71 %), while P-14 × LBG-5 also showed substantial yield superiority (81.77 %) and desirable specific combining ability (SCA) effects for earliness, lower nodal position of flowering, fruit attributes and yield components. P-14 and PK-3 were identified as superior general combiners, indicating their potential as valuable parental lines for future hybrid breeding programmes. The predominance of non-additive gene action for most growth and yield-related traits further supports heterosis breeding as an effective strategy for improving bitter gourd productivity. From a practical perspective, PK-3 × PK-2 and P-14 × LBG-5 represent promising genetic combinations for developing early, high-yielding hybrids. However, their superior performance should be validated before commercial utilisation. Future research could therefore focus on multi-location and multi-season evaluation, genotype × environment interaction and stability analyses, fruit quality and market acceptability, resistance to major biotic and abiotic stresses and the economic feasibility of hybrid seed production. Validation of consistent superiority across diverse environments would provide a stronger basis for advancing these hybrids towards commercial evaluation and potential release, while the superior parental lines could be further exploited in bitter gourd improvement programmes.

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Authors' contributions

DS 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. ASR contributed to creating figures and tables. MA provided materials, equipment and expertise. DK contributed to reviewing and editing. CS contributed to data organisation in Excel and data analysis. AK contributed to final review and corrections. R contributed to editing the manuscript and references. VS provided support in recording field data. H supported data recording during laboratory work. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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