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RESEARCH ARTICLE

Unlocking the genetic potential of bottle gourd (*Lagenaria siceraria* (Molina) Standl.): analyzing yield and agronomic traits through combining ability and heterosis

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Abstract

This study evaluated the combining ability and heterosis of fourteen genotypes using a Line × Tester mating design, aimed at identifying superior parental lines for enhancing agronomic traits in the *Kharif* 2023 season. The genotypes, comprising 10 lines and 4 testers, were crossed to generate 40 F1 hybrids, which were assessed alongside 14 parental genotypes and a commercial check in experimental field trials at Lovely Professional University during late summer 2024. The experiment was conducted using an alpha lattice design with two replications, focusing on 12 traits including days to flowering, fruit characteristics and yield. Analysis of variance (ANOVA) revealed highly significant differences for all traits, indicating substantial genetic variability among the genotypes. General combining ability (GCA) and specific combining ability (SCA) estimates were used to assess the genetic potential of the genotypes, with notable effects observed for traits like early flowering (GCA and SCA effects for DMF ranging from -3.48** to 2.53 and -10.60** to 5.88, DFF ranging from -4.05** to 3.70 and -10.60** to 4.93), vine length (GCA and SCA effects for VL ranging from -84.78 to 79.20** and -125.17 to 240.32**) and fruit yield (GCA and SCA effects for FYPP ranging from -1.28 to 0.97 and -4.32 to 6.97**). Heterosis analysis demonstrated significant positive heterosis for fruit yield per plant, with crosses such as N/06-40 × Punjab Round exhibiting impressive hybrid vigor. The study also identified distinct heterotic groups through dendrogram analysis, providing insights into the genetic dissimilarity among the genotypes. Overall, the findings underscore the importance of both additive and non-additive genetic effects in trait improvement and offer valuable guidance for future breeding strategies to optimize crop performance and yield.

Keywords: bottle gourd; combining ability; heterosis; line x tester; yield

Introduction

Bottle gourd (*Lagenaria siceraria*) holds significant importance in Sub-Saharan Africa (SSA) and Indian sub-continent for its versatile utility as a crop. Its leaves, fruits and seeds are prized for their nutritional value, contributing vital elements to diets in the region (1). While bottle gourd remains underexplored and underutilized in India, where commercial varieties are limited, diverse genetic resources in Africa and Asia offer potential for developing improved varieties through selective breeding (1). Notably, traits like flowering time, plant morphology and fruit characteristics exhibit considerable variation, presenting opportunities for breeding programs to enhance cultivar performance.

In India, bottle gourd holds culinary significance and is recognized for its medicinal properties, including anti-diabetic, anti-cancer and anti-inflammatory effects (2-4). Its nutritional richness and genetic diversity underscore its potential to contribute significantly to horticultural production in India. However, realizing this potential necessitates collaborative research involving experts across disciplines such as plant breeding, agronomy, genetics and food science. Such collaboration can facilitate knowledge exchange, germplasm sharing and innovative product development to meet diverse human needs and support the food and feed industry in India.

Combining ability refers to the ability of a genotype to transmit desirable traits to its offspring. It is categorized into GCA, which reflects the average performance of a genotype when crossed with several others and SCA, which indicates how well a specific cross performs compared to others. The study of combining ability and heterosis is crucial in plant breeding as it provides insights into the genetic potential of different genotypes for hybridization. Understanding these parameters allows breeders to select parent genotypes that will produce superior hybrids (1).

Heterosis, or hybrid vigor, describes the phenomenon where hybrid offspring exhibit enhanced traits compared to their parents. This can include increased growth rates, higher yields and improved resistance to diseases. Evaluating heterosis is essential for identifying crosses that can significantly outperform their parents in various agronomic traits. The integration of combining ability and heterosis assessments enables breeders to make informed decisions about which genotypes to utilize in breeding programs, ultimately leading to the development of high-performing cultivars (5).

The current study focuses on evaluating the combining ability and heterosis of fourteen selected bottle gourd genotypes using a Line x Tester mating design. This research aims to explain the genetic potential of these genotypes by assessing various agronomic traits.

Materials and Methods

14 genotypes were selected for the current study based on previous experiment data (data not presented). The genotypes selected for the study were based on the diversity analysis and at least one genotype from each cluster was selected along with *per se* performance of the genotypes. The selected genotypes were crossed according to Line X Tester mating design in *Kharif* 2023. Of the selected genotypes, 10 were lines and 4 were testers which produced a total of 40 F_1 hybrids. These 40 genotypes along with 14 parents and one commercial check were evaluated in field trials which were conducted in experimental fields, department of genetics and plant breeding at Lovely Professional University. The evaluation took place during the late summer 2024 (April). The experiment employed alpha lattice design with 5 blocks per replication, each block containing 11 genotypes and replicated twice (6). Each plot consisted of 2 rows with 3 plants in each row with plant-to-plant distance of 75 cm and row to row distance of 2 m. Application of FYM @ 20-25 tonnes/acre and 28 kg of N in two splits and irrigations were done at 6-7 days interval as outlined by PAU.

Data collection comprised of observations on 12 traits which includes days to first male flowering (DMF), days to first female flowering (DFF), sex ratio (SR), number of secondary branches (NSB), vine length (VL), fruit length (FL), fruit girth (FG), days to 1st harvest (D1H), days to 3rd harvest (D3H), average fruit weight (AFW), fruit flesh thickness (FFT) and fruit yield per plant (FYPP). Within each plot, three designated plants were tagged for observation and all measurements were recorded from these plants.

The analysis of variance for the experimental design was conducted using the “agricolae” (7) package in R-Studio, while the L x T mating design was analyzed with AGD-R (8). The relative importance of GCA and SCA effects was assessed using Baker’s Ratio (9) and later modified (10). Heterotic grouping based on GCA followed the method (11). Visualizations were created using both R-Studio and MS Excel.

Results

Analysis of variance

The present study aimed to evaluate the combining ability and heterosis of fourteen genotypes using a Line x Tester mating design, focusing on various agronomic traits. The findings reveal significant insights into the genetic potential and performance of these genotypes, contributing to the understanding of their importance in hybridization programs.

ANOVA for experimental design shows that mean sum of squares for treatments was highly significant for all the traits studied as shown in Table 1. These results are in strong conformity with previous studies (12-14). ANOVA for L x T mating design, further partitioned the sources of variation among treatments to parents and crosses which is further divided as lines and testers in parents. Mean sum of squares for treatments, parents, parents’ vs crosses, crosses and lines x testers were highly significant for all the traits. Lines showed significant value for VL, FL, FG, AFW and FYPP. On the other hand, testers showed significant values for DFF, SR, FG, D1H, AFW, FFT and FYPP and highly significant for FL (Table 2).

The ANOVA for mating design indicated highly significant differences among treatments for all traits, indicating the genetic variability present in the selected genotypes. The estimates of GCA and SCA further explained the genetic architecture underlying these traits. Notably, GCA effects were predominantly negative for traits such as DMF and DFF, indicating that early flowering is a desirable trait in this context. Genotype IC 92362 exhibited a significant negative GCA effect of -3.48 for DMF and -4.05 for DFF, suggesting its potential as a parent for early flowering traits. Previous studies are indicative of these results (12, 15).

Estimates of general combining ability

The estimates of GCA effects are summarized in Supplementary Table 1. For DMF, GCA effects ranged from -3.48 (IC 92362) to 2.53 (IC 371745). Significant negative effects were observed for IC 92362, followed by Pusa Meghdoot, IC 394739, VRBG-3 and N/06-40, while five parents showed significant positive effects. Similarly, DFF ranged from -4.05 (IC 92362) to 3.70 (IC 371745). Among the parents, IC 92362, VRBG-3, IC 284895 and Pusa Majiri exhibited significant negative effects, while three parents showed positive effects. The sex ratio (male: female) exhibited GCA effects ranging from -1.36 (IC 371745) to 2.53 (N/06-40). For D1H, GCA effects spanned -4.23 (N/06-40) to 3.65 (IC 284895). Negative effects were significant for N/06-40, followed by IC

Table 1. ANOVA of alpha lattice design (2 replications) for 12 studied traits

Source of variation	df	DMF	DFF	SR	NSB	VL	FL	FG	D1H	D3H	AFW	FFT	FYPP
Replication	1	0.04	0.33	0.04	0.23	943	0.23	0.23	11.14	1.5	2103	4.40	0.45
F-value		0.005	0.043	1.975	0.294	1.544	0.067	0.155	1.410	0.124	0.609	1.251	2.106
Treatments	54	59.5**	53.5**	10.6**	71.8**	28497**	268.5**	61.5**	49.7**	321.7**	309479**	124.5**	33.4**
F-value		59.53	53.47	10.653	71.84	28497	268.46	61.47	49.72	321.7	309479	124.96	33.40
Block	4	1.95	7.59	0.011	1.94	1451	1.57	3.65	4.56	4.2	1492	5.51	0.04
F-value		0.287	0.993	0.621	2.504	2.378	0.464	2.492	0.578	0.342	0.432	1.566	0.204
Rep:Block	4	2.20	5.42	0.018	0.98	1034	7.09	1.81	9.20	8.7	1345	8.44	0.29
F-value		0.323	0.709	0.963	1.261	1.694	2.094	1.238	1.165	0.699	0.390	8.44	1.362
Residuals	46	6.81	7.64	0.018	0.77	610	3.38	1.47	7.90	12.4	3454	3.52	0.21

*Significance at 5 % probability level; ** Significance at 1 % probability level

Table 2. ANOVA of LxT mating design

Source of variation	df	DMF	DFF	SR	NSB	VL	FL	FG	D1H	D3H	AFW	FFT	FYPP
Replications	1	0.03	0.37	0.03	0.22	942.58	0.22	0.22	11.13	1.53	2103.2	4.4	0.44
Treatments	54	58.7**	53.4**	10.6**	69.47**	28508**	265.7**	61.4**	50.5**	321.4**	308425.6**	124.6**	33.39**
Parents	14	59.05**	39.2**	10.5**	38.64**	22966**	227.61**	42.69**	17.61**	47.55**	158047.1**	65.14**	20.83**
Parents vs. Crosses	1	68.86**	44.82**	18.0**	107.7**	95948**	354.54**	315.27**	10.97*	11798**	2103015**	535.43**	497.66**
Crosses	39	58.44**	58.78**	10.46**	79.56**	28768**	277.14**	61.6**	62.7**	125.5**	316392**	135.42**	25.99**
Lines	3	27.03	35.93	1.78	48.53	54429*	345.38*	37.2*	15.56	32.97	251125.3*	9.70	58.38*
Testers	9	28.77	60.7*	13.82*	36.67	14625	445.07**	81.43*	66.13*	102.06	633048.0*	212.21*	25.02*
Lines x Testers	27	71.82**	60.69**	10.3**	97.31**	30631**	213.58**	57.71**	66.79**	143.59**	218092.5**	123.8**	22.72**
Error	54	6.84	7.49	0.05	97.23	692.73	6.24	1.72	7.41	11.78	4205.9	4.38	0.21
Total	109												

*Significance at 5 % probability level; ** Significance at 1 % probability level

393752, Avinash IV, IC 371745 and Punjab Round, while seven parents showed positive effects. When considering D3H, GCA effects ranged from -4.99 (N/06-40) to 6.01 (IC 284895). Significant negative effects were observed in N/06-40, IC 393752, Avinash IV, IC 371745 and Pusa Meghdoot, while five parents displayed positive effects. Negative GCA effects were generally desirable for traits such as DMF, DFF, SR, D1H and D3H. Notably, only IC 371745 showed a significant negative effect, whereas SEA-83 and N/06-40 exhibited positive effects. Similar results were also observed in previous studies (16, 17).

For number of secondary branches, the GCA range was -2.32 (Pusa Meghdoot) to 4.61 (SEA-83). SEA-83 had highly significant positive effects, followed by IC 284895, Punjab Round and Narendra Pooja, while four parents exhibited negative effects. In case of vine length, GCA effects varied widely, from -84.78 (SEA-83) to 79.20 (IC 371745). Highly significant positive effects were noted for IC 371745, followed by Pusa Meghdoot, IC 92362, Avinash IV and IC 284895, while six parents showed negative effects. For fruit girth, the GCA effects ranged from -4.72 (IC 393752) to 5.01 (SEA-83). Significant positive effects were observed in SEA-83, followed by VRBG-71, IC 92362, IC 371745, Pusa Majiri, Narendra Pooja and Avinash IV, while seven parents exhibited negative effects. The GCA effects for fruit girth ranged from -1.12 (IC 393752) to 1.24 (VRBG-3). VRBG-3 and VRBG-71 showed significant positive effects, while only IC 393752 had significant negative effects. For average fruit weight, GCA effects ranged from -216.59 (IC 394739) to 272.06 (VRBG-71). Highly significant positive effects were observed for VRBG-71, followed by IC 92362, SEA-83, VRBG-3 and Pusa Majiri, while seven parents had significant negative effects. In the case of fruit flesh thickness, GCA effects varied between -6.24 (SEA-83) and 7.90 (VRBG-71). Significant positive effects were noted for VRBG-71, followed by IC 393752, IC 394739 and IC 284895, while five parents had negative effects. Finally, for fruit yield, GCA effects ranged from -1.28 (Punjab Round) to 0.97 (Pusa Majiri). Notably, no crosses exhibited significant positive GCA effects, while Punjab Round was the only parent showing significant negative effects.

The GCA effects revealed that certain genotypes, like IC 371745, showed highly significant positive effects on vine length (VL) with a GCA of 79.20, while SEA-83 had a notable positive effect on the number of secondary branches (NSB) with a GCA of 4.61. This suggests that these lines may serve as valuable parents in breeding programs aimed at improving these traits. Conversely, genotypes with significant negative GCA effects for traits like D1H highlight their potential for early maturation, which is crucial for shortening the crop duration. Previous studies support the results observed (16, 18).

Estimates of specific combining ability

The SCA effects for various traits are detailed in the Supplementary Table 2. Negative SCA effects are generally desirable for traits like DMF, DFF, SR, D1H and D3H. For DMF, SCA effects ranged from -10.60 (IC 284895 × Pusa Majiri) to 15.85 (VRBG-3 × Narendra Pooja). The cross IC 284895 × Pusa Majiri demonstrated highly significant negative SCA effects. In DFF, the SCA effects spanned -10.16 (IC 92362 × Pusa Meghdoot) to 9.20 (VRBG-71 × Narendra Pooja). Highly significant negative effects were observed in IC 92362 × Pusa Meghdoot, making it a favorable combination for early flowering. The sex ratio (male:female) displayed SCA effects ranging from -3.86 (IC 284895 × Pusa Majiri) to 1.59 (N/06-40 × Pusa Meghdoot). Among these, IC 284895 × Pusa Majiri demonstrated the most desirable outcome with a highly significant negative effect. For D1H, SCA effects varied between -13.64 (N/06-40 × Pusa Meghdoot) and 16.53 (IC 92362 × Pusa Meghdoot). The cross N/06-40 × Pusa Meghdoot showed the most favorable early harvesting effect, with a highly significant negative value. Similarly, in D3H, effects ranged from -13.64 (N/06-40 × Pusa Meghdoot) to 25.13 (IC 284895 × Pusa Majiri). The combination N/06-40 × Pusa Meghdoot was again desirable for promoting early harvests. Similar results were observed in early findings (19, 20).

For AFW, the SCA effects ranged widely from -473.11 (VRBG-3 × Punjab Round) to 460.18 (VRBG-3 × Narendra Pooja). Crosses like VRBG-3 × Narendra Pooja were highly significant for increasing fruit weight. For VL, effects ranged from -137.55 (IC 394739 × Pusa Majiri) to 240.32 (SEA-83 × Pusa Majiri). Highly significant positive effects were observed in SEA-83 × Pusa Majiri, indicating its potential for longer vines. The NSB exhibited SCA effects from -11.44 (IC 92362 × Pusa Meghdoot) to 11.60 (VRBG-71 × Narendra Pooja). The cross VRBG-71 × Narendra Pooja showed the highest positive effect, favoring branch development. For FG, the range was -6.96 (VRBG-3 × Punjab Round) to 11.64 (VRBG-3 × Narendra Pooja). The combination VRBG-3 × Narendra Pooja was highly significant for promoting larger fruits. FFT exhibited SCA effects between -9.51 (IC 394739 × Pusa Majiri) and 8.41 (IC 284895 × Pusa Meghdoot). Highly significant positive effects were observed in crosses like IC 284895 × Pusa Meghdoot, favoring thicker fruit flesh. Finally, FYPP, SCA effects spanned -3.60 (IC 284895 × Pusa Meghdoot) to 7.98 (SEA-83 × Punjab Round). The combination SEA-83 × Punjab Round showed a significant positive effect, highlighting its potential for high yield. These results are in conformity with previous studies (21, 22).

The SCA analysis provided crucial insights into the performance of specific hybrid combinations. For instance, the cross IC 284895 × Pusa Majiri demonstrated highly significant negative SCA effects for DMF (-10.60), indicating its potential as an early maturing hybrid. Such hybrids could be advantageous in regions with shorter growing seasons or where early market access is prioritized. Moreover, the SCA effects for fruit-related traits such as AFW showed promising results for combinations like VRBG-3 × Narendra Pooja, which had an SCA effect of 460.18, indicating its potential to enhance fruit weight significantly. This suggests that specific hybrid pairings can significantly enhance fruit quality parameters, which are essential for marketability. These results are in conformity with previous studies (21, 22).

GCA variance for all the traits were lower as compared to the SCA variance (Table 3, Fig. 1) demonstrating the importance of non-additive gene action. The Baker's ratio is a metric that quantifies the proportion of total variance attributed to additive gene action. Higher values (close to 1) indicate predominance of additive effects, whereas lower values suggest dominance or non -additive gene action. Amongst the traits studied, DFF, SR, VL, FL, D1H, D3H, AFW and FFT showed moderate Baker's ratio which highlights the importance of both additive and non-additive gene action whereas DMF, NSB, FG and FYPP had low Baker's ratio indicating the importance of non-additive gene action. These results are similar with the previous studies (20, 23).

Heterosis

Across the various traits studied, significant variations in mid-parent heterosis and heterobeltiosis were observed, highlighting the performance of certain crosses (Supplementary Table 3). For DMF, heterosis ranged from -21.36 to 16.55, with N/06-40 x Punjab Round leading the pack for early flowering, closely followed by N/06-40 x Narendra Pooja and IC 284895 x Pusa Majiri. Heterobeltiosis showed a similar trend, with the top three being N/06-40 x Punjab Round, IC 92362 x Narendra Pooja and IC 284895 x Pusa Majiri. Impressively, 23 crosses exhibited negative mid-parent heterosis, while 27 showed negative heterobeltiosis.

For DFF, the range of heterosis extended from -24.48 to 16.79. The fastest flowering was recorded in IC 284895 x Pusa Majiri, with IC 92362 x Narendra Pooja and IC 284895 x Punjab Round trailing closely behind. Meanwhile, heterobeltiosis values varied between -4.05 and 14.48, where the top-performing crosses mirrored the mid-parent heterosis results. A total of 25 and 29 crosses, respectively, showed negative heterosis and heterobeltiosis. SR showcased the most dramatic fluctuations, with heterosis spanning from -73.72 to 174.32. The cross IC 394739 x Pusa Meghdoot achieved the most desirable lower sex ratio, accompanied by N/06-40 x Pusa Meghdoot and IC 92362 x Pusa Meghdoot. Heterobeltiosis also ranged broadly, from -82.22 to 139.20, with IC 394739 x Pusa Meghdoot again topping the list.

In terms of D1H, heterosis ranged from -13.04 to 16.55. IC 92362 x Pusa Meghdoot emerged as the frontrunner for early harvesting, followed by IC 394739 x Narendra Pooja and N/06-40 x Pusa Majiri. Heterobeltiosis was similarly varied, with the top crosses being IC 92362 x Pusa Meghdoot, VRBG-3 x Pusa Majiri and IC 394739 x Pusa Meghdoot. A notable 21 crosses demonstrated negative mid-parent heterosis, while 29 crosses exhibited negative heterobeltiosis.

For D3H, heterosis and heterobeltiosis reflected a strong negative trend, with nearly all 39 out of 40 crosses showing negative values. However, IC 393752 x Pusa Majiri, N/06-40 x Pusa Majiri and IC 92362 x Pusa Meghdoot were among the most consistent early performers.

Traits like the NSB revealed heterosis values ranging from -62.67 to 116.93, where IC 92362 x Pusa Meghdoot stood out as the top performer, followed by IC 394739 x Pusa Meghdoot and IC 371745 x Pusa Meghdoot. For vine length (VL), N/06-40 x Punjab Round demonstrated the highest heterosis (75.33), with VRBG-71 x Punjab Round and IC 92362 x Pusa Meghdoot also excelling.

Fruit-related traits also showed intriguing patterns. For FL, VRBG-71 x Pusa Majiri recorded the highest heterosis (99.34), while SEA-83 x Pusa Meghdoot and VRBG-71 x Pusa Meghdoot followed suit. Similarly, VRBG-71 x Punjab Round emerged as the best for FG, with strong competition from IC 393752 x Pusa Meghdoot and VRBG-3 x Punjab Round. AFW displayed a massive range in heterosis (-38.56 to 181.09), with IC 393752 x Pusa Meghdoot leading, while VRBG-71 x Pusa Meghdoot and Avinash IV x Pusa Meghdoot secured the next spots.

Finally, fruit yield per plant, mid-parent heterosis ranged from -2.6 to 171.88 with N/06-40 x Punjab Round having highest heterosis followed by N/06-40 x Pusa Majiri and SEA-83 x Pusa Meghdoot while heterobeltiosis ranged from -9.74 to 162.59. The

Table 3. Estimates of GCA variance and SCA variance along with Baker's ratio

	DMF	DFF	SR	NSB	VL	FL	FG	D1H	D3H	AFW	FFT	FYPP
SCA Var	19.67	15.38	3.32	29.66	8777.81	61.26	18.30	19.33	40.02	66725.20	33.13	7.95
GCA Var	2.80	5.67	1.22	3.73	1900.82	10.58	0.53	5.90	9.21	17889.25	18.48	0.23
Baker's Ratio	0.12	0.27	0.27	0.11	0.18	0.15	0.03	0.23	0.19	0.21	0.36	0.03

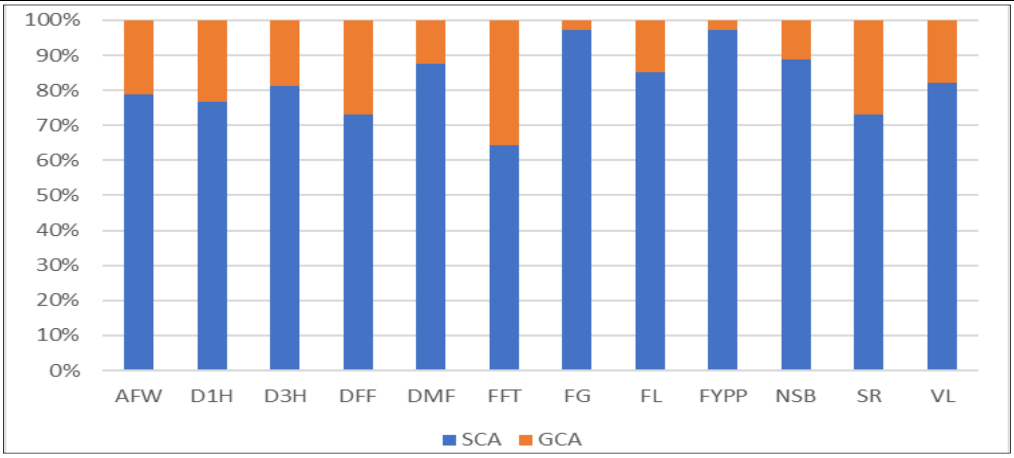

Fig. 1. Relative proportion of SCA variance and GCA variance.

best three crosses were N/06-40 x Punjab Round, VRBG-3 x Narendra Pooja and SEA-83 x Punjab Round. Fruit yield per plant showcased remarkable positive heterosis for 39 out of 40 crosses.

The study observed significant heterosis across various traits, particularly in FYPP, where nearly all crosses exhibited positive mid-parent heterosis. The cross N/06-40 × Punjab Round achieved an impressive mid-parent heterosis of 171.88 for FYPP, underscoring the potential of hybrid vigor in improving yield outcomes. This finding supports the notion that hybridization can effectively exploit genetic diversity among parental lines. The significant variations in heterosis values for the sex ratio also warrant further examination. The cross IC 394739 × Pusa Meghdoot achieved a notably lower sex ratio with a heterosis value of -73.72, which could enhance reproductive efficiency in subsequent generations. Such insights are vital for breeding strategies aimed at optimizing yield through improved sex ratios. Previous studies have documented the results which support the findings of our observations (13, 16, 22, 24).

Heterotic grouping

A dendogram was constructed using the heterotic grouping using GCA method to classify 14 genotypes into 4 clusters at 40 % rate of dissimilarity with cluster I have only one genotype (SEA-83), while cluster II had three genotypes, cluster III had four genotypes and cluster IV had six genotypes (Table 4, Fig. 2).

The dendrogram constructed from GCA estimates revealed distinct heterotic groups among the genotypes, indicating varying levels of genetic dissimilarity. The identification of clusters provides a framework for targeted breeding efforts, allowing breeders to select appropriate parents based on their grouping and performance traits. For example, cluster I containing only SEA-83 may indicate its unique genetic makeup that could be leveraged in future breeding programs. Similar studies have been carried out which supports these results (25).

Conclusion

This study assessed the combining ability and heterosis of fourteen genotypes through a Line x Tester mating design, revealing valuable insights into their genetic potential for various agronomic traits. The findings highlighted the importance of GCA and SCA in identifying superior parental lines for breeding programs. Genotypes IC 92362 and IC 371745 demonstrated significant contributions to early flowering and vine length, respectively, indicating their potential as key parents in future breeding efforts. Crosses IC 394739 x Pusa Meghdoot followed by SEA-83 x Pusa Majiri and VRBG-3 x Narendra Pooja was considered the best crosses in the current study. The observed heterosis across multiple traits, particularly in fruit yield per plant, underscores the effectiveness of hybridization in enhancing crop performance. The identification of distinct heterotic groups among the genotypes further provides an outline for targeted breeding programs. Overall, this research emphasizes the critical role of genetic evaluation in crop improvement and suggests that further studies should explore these findings across diverse environments to optimize breeding strategies and maximize agricultural productivity. However, these results can be further strengthened by conducting additional experiments in different locations and/or multiple seasons.

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Authors' contributions

APB carried out the field experiments and drafted the manuscript. TC interpreted the results and participated in drafting the manuscript. ND conceptualization of the experiment and participated in drafting the manuscript, HA carried out the data analysis and participated in the drafting the manuscript. All authors read and approved the final manuscript.

Table 4. Clusters based on heterotic grouping using GCA

Cluster	Genotypes
Cluster I	SEA-83
Cluster II	IC 92362, IC 284895, VRBG-3
Cluster III	N/06-40, Punjab Round, IC 394739, IC 393752
Cluster IV	VRBG-71, IC 371745, Avinash IV, Narendra Pooja, Pusa Majiri, Pusa Meghdoot

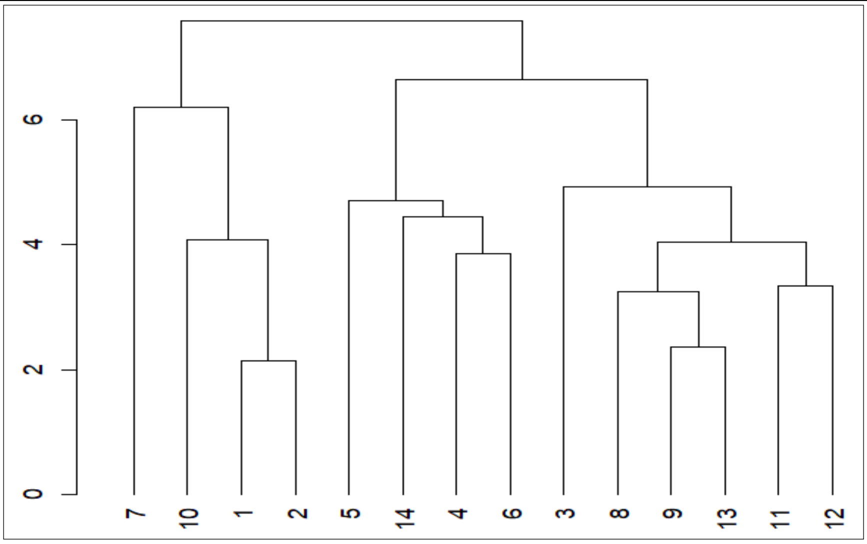

Fig. 2. Dendogram based on Ward's minimum variance for GCA values.

Compliance with ethical standards

Conflict of interest: Authors declare no conflict of interest.

Ethical issues: None

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