



RESEARCH ARTICLE

Combining ability and genetic architecture of yield and quality traits in bottle gourd (*Lagenaria siceraria* (Mol.) Standl.)

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Abstract

Bottle gourd (*Lagenaria siceraria* (Mol.) Standl.) is an important cucurbitaceous vegetable crop widely cultivated in tropical and subtropical regions due to its high nutritional value, adaptability, consumer preference and potential for yield improvement through heterosis breeding. The genetic improvement of bottle gourd requires a clear understanding of the relative contribution of additive and non-additive gene that govern yield and quality traits. The present investigation assessed general combining ability (GCA) and specific combining ability (SCA) in seven diverse parental lines and their 21 F₁ hybrids developed through a full diallel mating design (excluding reciprocals). The experimental material comprising seven parental lines and 21 F₁ hybrids was evaluated in a randomised complete block design (RCBD) with 3 replications for 10 agronomic and quality traits. Analysis of variance (ANOVA) revealed significant GCA and SCA effects for most traits, including fruit length (83.05 and 10.80), fruit girth (20.31 and 3.79), yield (183.2 and 760.3) and total soluble solids (0.11 and 0.19), respectively, with SCA variance predominating for yield and its major components, indicating the importance of dominance and epistatic interactions. Among parents, BRBG 65 exhibited desirable GCA effects for primary branches per vine (1.06), vine length (0.27) and fruit length (3.20), while BRBG 190 showed positive GCA effects for fruit girth (1.50) and yield (21.65), identifying them as superior general combiners for yield and quality attributes. Among the hybrids, BRBG 65 × Punjab Komal recorded high positive SCA effects for yield (16.25), fruit girth (2.81) and earliness for first fruit harvest (-4.82), whereas BRBG 51-2 × BRBG 190 exhibited high and desirable SCA effects for fruit length (6.89) and yield (10.16). The hybrid BRBG 21-2 × Pusa Naveen also showed significant positive SCA effects for yield (9.75) and total soluble solids (0.71), demonstrating substantial heterotic potential. The findings of the present study indicated the predominance of non-additive gene action and suggested that hybrid breeding could be effectively utilised for yield enhancement in bottle gourd. Furthermore, the identified superior parents and promising hybrids may serve as valuable genetic resources for future hybrid development and population improvement programmes under eastern Indian agro-climatic conditions.

Keywords: additive gene; cucurbits; diallel analysis; general combining ability; gene action; heterosis; hybrids

Introduction

Bottle gourd (*Lagenaria siceraria* (Mol.) Standl.), belonging to the family Cucurbitaceae, is believed to have originated in Africa and is now widely distributed and cultivated across tropical and subtropical regions of the world, particularly in India, where it is extensively grown in states such as Uttar Pradesh, Bihar, West Bengal, Odisha, Madhya Pradesh, Karnataka and Maharashtra. In India, bottle gourd is cultivated over an area of approximately 1.85–1.86 lakh hectares with an annual production of about 30.5–30.7 lakh tonnes and an average productivity of around 16.5–16.7 t ha⁻¹, reflecting its economic importance, its adaptability, high productivity and culinary versatility make it a key component of vegetable-based cropping systems. The crop is valued not only for fresh consumption but also for its nutritional attributes, including dietary fibre and bioactive compounds (1). The species is diploid (2n = 22) and predominantly cross-pollinated due to its monoecious flowering habit and high insect-mediated pollination rate, which may reach up to 80 % (2). These biological characteristics facilitate

genetic recombination and provide ample opportunity for exploiting heterosis through hybrid breeding. However, the effective utilisation of heterosis depends on a precise understanding of the genetic control of yield and its constituent traits.

Yield in bottle gourd is a complex quantitative trait influenced by multiple interrelated components such as fruit length, fruit girth, average fruit weight and number of fruits per plant (3). Since yield does not follow a simple Mendelian inheritance pattern, its improvement requires an assessment of both additive and non-additive genetic effects (4, 5). Earlier genetic studies in cucurbits and other vegetable crops have demonstrated that dominance and epistatic interactions often play a major role in determining yield performance (6, 7).

Combining ability analysis provides an effective framework for dissecting genetic variance into general combining ability (GCA), associated with additive gene effects and specific combining ability (SCA), which reflects non-additive gene action (8, 9). This approach has been widely applied in vegetable crops to identify superior

parents and hybrid combinations (10, 11). Since heterosis is largely governed by non-additive gene effects, combining ability analysis serves as an important tool for identifying parental combinations capable of producing superior hybrids with enhanced yield and quality traits. In bottle gourd, several studies have reported significant GCA and SCA effects for yield and quality traits, with a frequent predominance of SCA variance, indicating the suitability of hybrid breeding strategies (12–14). However, efficient hybrid development in bottle gourd is constrained by its monoecious flowering behaviour, lack of synchronisation in flowering among parental lines, strong environmental influence on sex expression and the laborious process involved in controlled pollination and hybrid seed production. Recent combining ability studies in bottle gourd have demonstrated substantial variability for quantitative traits and highlighted the importance of both additive and non-additive gene effects, providing a strong basis for parent selection and hybrid breeding (15).

Despite these efforts, information on the combining ability of locally adapted germplasm under eastern Indian agro-climatic conditions remains limited. Moreover, the identification of parents possessing stable additive effects alongside hybrids expressing high non-additive interactions is essential for designing efficient breeding programs (16, 17). Therefore, the present study was undertaken to (i) estimate GCA and SCA effects for yield and quality traits in bottle gourd, (ii) identify superior parents and promising hybrid combinations and (iii) elucidate the nature and magnitude of gene action governing these traits for their effective utilisation in future breeding programs.

Materials and Methods

Experimental material and crossing design

Seven genetically diverse parental lines of bottle gourd BRBG 51-2, BRBG 21-2, BRBG 65, BRBG 190, BRBG 42-2, Pusa Naveen and Punjab Komal were collected from the Department of Vegetable Science, Bihar Agricultural University, Indian Agricultural Research Institute and Punjab Agricultural University. The parental lines were selected based on phenotypic diversity, yield potential, fruit shape and other important agronomic traits. Details regarding the source and salient characteristics of the parental lines are presented in Table 1. The parents were crossed in a half-diallel mating design following Griffing's Method II, Model I, excluding reciprocal crosses, resulting in 21 F_1 hybrid combinations. Hybridisation was carried out manually during the flowering period. Healthy flower buds expected to open on the following day were selected in both male and female parents during evening hours and covered with butter paper bags to avoid unwanted pollination. Emasculation was not required due to the unisexual nature of bottle gourd flowers. On the following morning, freshly opened staminate flowers from the male parent were collected and pollen was manually transferred onto the stigma of selected pistillate flowers. The pollinated flowers were immediately re-bagged and tagged properly for identification and seed collection.

Experimental layout

The parental lines and F_1 hybrids were evaluated during the winter season at the Vegetable Research Farm, Bihar Agricultural University,

Sabour. The experiment was laid out in a randomised complete block design (RCBD) with 3 replications. Each experimental plot was maintained with a spacing of 2.5 m between rows and 0.5 m between plants. All parental lines and F_1 hybrids were grown under recommended agronomic practices for bottle gourd cultivation. The experimental field was thoroughly prepared by ploughing and levelling, followed by the incorporation of well-decomposed farmyard manure at 20 t ha⁻¹ before sowing. Recommended doses of fertilisers (N : P : K at 120 : 60 : 60 kg ha⁻¹) were applied, with half of nitrogen (N) and full doses of phosphorus (P) and potassium (K) applied as basal, while the remaining nitrogen was top-dressed in 2 equal splits at vine development and flowering stage. Irrigation was provided at regular intervals depending upon crop requirement and prevailing weather conditions. Intercultural operations were carried out as per standard recommendations. Need-based applications of recommended insecticides and fungicides were applied to control fruit fly, red pumpkin beetle, powdery mildew and downy mildew.

Sampling and data collection

Five healthy and competitive plants were randomly selected and tagged from each plot in each replication to record observations and to minimise environmental variation. Phenological traits such as days to anthesis of first staminate and pistillate flowers were recorded on a plot basis. Vegetative traits, including vine length and number of primary branches per vine, were measured at peak vegetative growth stage (60 days after sowing (DAS)). Fruits were harvested at marketable maturity, approximately 12–15 days after fruit set depending upon genotype and observations on fruit-related traits were recorded from marketable fruits harvested at physiological maturity. Yield per plot was converted to yield per hectare. Total soluble solids (°Brix) were measured using a digital hand refractometer following standard procedures (17).

Data was collected on the following traits using standard descriptors and procedures. Days to anthesis of first staminate flower was counted from sowing to first male flower opening. Days to anthesis of first pistillate flower recorded from sowing to first female flower opening. Primary branches per vine are counted at peak vegetative stage (60 DAS). Vine length (m) measured from the base to the terminal growing point at final harvest. Fruit length (cm) and fruit girth (cm) measured using a digital vernier caliper on marketable fruits. Days to first fruit harvest recorded from sowing to first harvestable fruit. Average fruit weight (kg) calculated as the mean weight of harvested fruits per plant. Yield (t ha⁻¹) extrapolated from plot yield to hectare basis. Total soluble solids (TSS) were estimated at the marketable maturity stage using fresh fruit pulp extracted from randomly selected fruits. The juice sample was placed on the prism of a digital hand refractometer and readings were recorded at room temperature and expressed as °Brix, following the official methods of analysis (18).

Statistical analysis

The data recorded on different quantitative traits were subjected to ANOVA following the RCBD to evaluate the significance of genotypic differences. The significance of variance was evaluated at 5 % and 1 % probability levels. Combining ability parameters were estimated using Griffing's Method II, Model I (fixed effects), which has been widely applied for dissecting additive and non-additive gene effects in yield-related traits across crops (9, 17, 19).

Table 1. Distinguishing features and source of parental lines

Parental line	Source	Important characters	Representative photograph
BRBG 51-2	BAU, Sabour	Long, bottle-shaped fruits; late maturity; high yield	
BRBG 21-2	BAU, Sabour	Early, cylindrical fruits; promising yielder	
BRBG 65	BAU, Sabour	Long, bottle-shaped fruits; late but high yielding	
BRBG 190	BAU, Sabour	Small, round fruits; distinctive seed colour and size	
BRBG 42-2	BAU, Sabour	Club-shaped, deep green striped fruits; good cooking quality	
Pusa Naveen	IARI, New Delhi	Small, cylindrical fruits; early; high fruit number	
Punjab Komal	PAU, Ludhiana	Small, round fruits; very early; high fruit number	

IARI: Indian Agricultural Research Institute; PAU: Punjab Agricultural University; BAU: Bihar Agricultural University.

Results

Analysis of variance for combining ability

The analysis of variance (ANOVA) revealed highly significant differences among genotypes for all the traits studied, indicating the presence of substantial genetic variability in the experimental material (Table 2). Significant GCA mean squares were observed for primary branches per vine (8.19), vine length (0.46), fruit length (83.05), fruit girth (20.31), average fruit weight (0.02) and TSS (0.11), indicating the importance of additive gene effects in the inheritance of these traits. Similarly, significant SCA mean squares were recorded for days to anthesis of first staminate flower (8.17), days to anthesis of first pistillate flower (11.82), primary branches per vine (2.78), vine length (0.46), fruit length (10.80), days to first fruit harvest (16.33), fruit girth (3.79), average fruit weight (0.00), yield (760.3) and TSS (0.19), suggesting the involvement of non-additive gene effects. However, the magnitude of SCA variance was considerably higher than GCA variance for important traits such as yield (760.3 vs. 183.2), days to first fruit harvest (16.33 vs. 10.20) and TSS (0.19 vs. 0.11), indicating the predominance of non-additive gene action.

General combining ability effects

The estimates of GCA effects revealed that no single parent was a good general combiner for all the traits, highlighting the complex and polygenic nature of yield and its components (Table 3). Among the parents, BRBG 65 exhibited significant positive GCA effects for days to anthesis of first staminate flower (1.54), days to anthesis of first pistillate flower (1.28), primary branches per vine (1.06), vine length (0.27) and fruit length (3.20), indicating its potential to contribute favourable additive alleles for vegetative growth and fruit development. BRBG 190 showed significant positive GCA effects for fruit girth (1.50) and yield (21.65), suggesting its usefulness for improving fruit size-related traits. Punjab Komal exhibited desirable negative GCA effects for days to first fruit harvest (-1.98), indicating its usefulness for earliness, along with significant positive GCA effects for fruit girth (2.40). Similarly, BRBG 51-2 showed significant positive GCA effects for vine length (0.23) and fruit length (3.54).

Specific combining ability effects

Several hybrid combinations exhibited significant and desirable SCA effects for yield and its associated traits (Table 4). Notably, BRBG 65 × Punjab Komal and BRBG 51-2 × BRBG 190 showed high positive SCA effects for yield (16.25), along with desirable effects for fruit girth (2.81) and earliness for first fruit harvest (-4.82), indicating strong non-additive gene interactions. Similarly, BRBG 51-2 × BRBG 190 showed high positive SCA effects for fruit length (6.89) and yield (10.16), while BRBG 21-2 × Pusa Naveen exhibited significant positive SCA effects for yield (9.75) and TSS (0.71). The cross BRBG 65 × BRBG 42-2 also recorded significant positive SCA effects for yield (7.53) and fruit girth (2.09). Interestingly, high SCA effects were often observed in crosses involving parents with moderate or even low GCA effects, suggesting that superior hybrid performance was not solely dependent on the general combining ability of the parents.

Discussion

Bottle gourd is a highly demanded vegetable crop in India and the development of high-yielding hybrids with desirable agronomic and quality traits is essential for enhancing productivity. The present investigation revealed significant genetic variability among parents and hybrids for all the traits studied, indicating ample scope for genetic improvement. The significance of both GCA and SCA effects for most traits suggested that yield and quality traits in bottle gourd are governed by a combination of additive and non-additive gene actions, as previously reported in bottle gourd and other cucurbits (12–15, 20–23).

The predominance of SCA variance over GCA variance for yield and its major components clearly indicated the major role of non-additive gene action, including dominance and epistasis, in the inheritance of these traits. This finding supports the suitability of hybrid breeding as an effective strategy for yield improvement in bottle gourd and corroborates previous reports highlighting the importance of non-additive effects in exploiting heterosis (6, 7, 13, 14, 21, 24, 25).

Table 2. Analysis of variance (ANOVA) for combining ability (general combining ability (GCA) and specific combining ability (SCA)) in bottle gourd

Source of variation	DF	Days to anthesis of first staminate flower	Days to anthesis of first pistillate flower	Primary branches / vine	Vine length (m)	Fruit length (cm)	Days to first fruit harvest	Fruit girth (cm)	Average fruit weight (kg)	Yield (t/ha)	TSS (°Brix)
GCA	6.00	8.63	4.67	8.19**	0.46**	83.05**	10.20	20.31**	0.02**	183.2	0.11**
SCA	21.00	8.17*	11.82**	2.78**	0.46**	10.80**	16.33**	3.79**	0.00**	760.3**	0.19**
Error	27.00	3.56	3.66	1.04	0.12	1.01	5.87	0.96	0.00	77.5	0.01

*-Significant at 5 % probability level; **- Significant at 1 % probability level; GCA: general combining ability; SCA: specific combining ability; DF: degrees of freedom; TSS: total soluble solids.

Table 3. Estimates of general combining ability (GCA) effects of parents for ten characters in bottle gourd

Source of variation	Days to anthesis of first staminate flower	Days to anthesis of first pistillate flower	Primary branches / vine	Vine length (m)	Fruit length (cm)	Days to first fruit harvest	Fruit girth (cm)	Average fruit weight (kg)	Yield (q/ha)	TSS (°Brix)
BRBG 51-2	-0.90	-0.21	-0.45	0.23*	3.54*	0.32	-1.98**	0.05	3.32	-0.11
BRBG 21-2	-0.36	0.61	0.95*	0.14	0.98**	1.01	-0.88**	0.00	-16.70	0.06
BRBG 65	1.54*	1.28*	1.06*	0.27*	3.20**	0.56	0.03	0.07	6.19	-0.17
BRBG 190	0.37	-0.52	-1.26**	-0.34*	-3.86**	-0.88	1.50**	-0.07	21.65	-0.04
BRBG 42-2	-0.99	-0.53	-0.48	-0.07	-0.19	0.17	-0.20	-0.02	-4.92	0.11
Pusa Naveen	0.96	0.07	-0.76*	-0.02	0.39	0.81	-0.88**	-0.01	8.54	0.12
Punjab Komal	-0.63	-0.71	0.93*	-0.21	-4.06**	-1.98*	2.40**	-0.06	-18.09	0.05
S.E. (gi)	1.43	1.44	0.77	0.26	0.76	1.83	0.74	0.03	21.02	0.08
S.E. (gi-gj)	2.18	2.21	1.18	0.39	1.16	2.79	1.13	0.04	32.11	0.12

*-Significant at 5 % probability level; **- Significant at 1 % probability level; TSS: total soluble solids.

Table 4. Estimates of specific combining ability (SCA) effects of F₁ hybrids for ten characters in bottle gourd

Source of variation	Days to anthesis of first staminate flower	Days to anthesis of first pistillate flower	Primary branches /vine	Vine length (m)	Fruit length (cm)	Days to first fruit harvest	Fruit girth (cm)	Average fruit weight (kg)	Yield (t/ha)	TSS (°Brix)
BRBG 51-2 × BRBG 21-2	-1.42	-1.25	-0.58	0.13	-3.43**	-1.50	0.34	-0.03	9.40**	0.18
BRBG 51-2 × BRBG 65	2.94	-1.12	0.14	-1.27**	3.36**	-1.88	-3.16**	0.13**	6.07*	0.40**
BRBG 51-2 × BRBG 190	-2.83	-2.31	0.62	0.08	6.89**	-1.88	-1.74	0.04	10.16**	-0.51**
BRBG 51-2 × BRBG 42-2	-0.38	7.22**	1.52	0.40	3.24**	3.99	-1.45	-0.02	-10.78	0.26*
BRBG 51-2 × Pusa Naveen	3.37	-3.71*	0.45	-0.10	-0.18	-0.54	0.52	0.13**	7.23	0.23*
BRBG 51-2 × Punjab Komal	-0.10	-2.43	-1.23	-0.66*	2.05*	-4.86*	-0.48	0.04	0.03	-0.51**
BRBG 21-2 × BRBG 65	3.05	1.29	-2.92**	-1.50**	-4.09**	1.37	0.89	-0.07*	-9.69**	0.34**
BRBG 21-× BRBG 190	-3.64*	1.34	0.89	0.43	0.48	6.29**	0.55	0.06	2.28	0.46**
BRBG 21-2 × BRBG 42-2	-3.24	1.52	1.62	0.38	2.25*	2.01	-0.59	0.01	4.54	-0.13
BRBG 21-2 × Pusa Naveen	0.86	-1.10	0.73	-0.47	-2.58**	4.52*	-3.13**	0.01	9.75**	0.71**
BRBG 21-2 × Punjab Komal	3.91	-1.11	-0.46	-0.15	1.89*	-0.59	-0.79	0.06	0.22	0.08
BRBG 65 × BRBG 190	1.18	-4.17*	0.28	1.10**	-2.18*	-4.52	-0.59	-0.06	5.87*	-0.75**
BRBG 65 × BRBG 42-2	2.90	-2.42	1.17	0.29	0.12	-0.18	2.09*	-0.06	7.53**	-0.78**
BRBG 65 × Pusa Naveen	2.21	3.16	3.62**	0.39	2.67**	3.39	0.91	-0.04	-1.02	0.02
BRBG 65 × Punjab Komal	-3.54	-2.73	1.77	0.67*	1.44	-4.82*	2.81**	0.04	16.25**	0.35**
BRBG 190 × BRBG 42-2	2.61	-4.06*	1.82	-0.43	1.37	-4.96*	0.36	0.05	4.14	-0.08
BRBG 190 × Pusa Naveen	0.53	2.63	-0.57	-0.82*	1.53	1.96	-1.19	-0.03	-8.80**	0.31**
BRBG 190 × Punjab Komal	3.85	2.66	1.08	0.19	0.58	4.82	0.21	-0.03	0.90	-0.42**
BRBG 42-2 × Pusa Naveen	-3.17	-4.64*	-1.18	0.22	-1.05	-6.40**	2.83**	-0.03	6.01*	-0.24*
BRBG 42-2 × Punjab Komal	-0.15	-2.81	-0.03	-0.41	0.60	3.35	-2.89**	0.05	-5.28*	0.43**
Pusa Naveen × Punjab Komal	0.88	-2.59	-0.25	-0.29	1.04	1.68	-1.77	-0.05	-2.03	0.02
S.E. (gi)	3.53	3.58	1.91	0.64	1.88	4.53	1.84	0.07	5.12	0.20
S.E. (gf-gj)	5.25	5.32	2.84	0.95	2.79	6.74	2.73	0.10	7.74	0.29

*- Significant at 5 % probability level; **- Significant at 1 % probability level; TSS: total soluble solids.

Although no single parent was identified as a good general combiner for all traits, BRBG 65 and BRBG 190 emerged as valuable parents due to their significant positive GCA effects for several important traits. These parents can be effectively utilised in population improvement programs aimed at accumulating favourable additive alleles through recurrent selection or pedigree breeding approaches (4, 5, 16, 26).

The identification of superior hybrids such as BRBG 65 × Punjab Komal and BRBG 51-2 × BRBG 190, which exhibited high SCA effects for yield and quality traits, highlights the importance of specific parental combinations in achieving superior hybrid performance. The occurrence of high SCA in crosses involving parents with low or moderate GCA further emphasises the role of non-additive gene interactions in hybrid vigour, a phenomenon well documented in cucurbits and other cross-pollinated crops (8, 9, 12, 22, 25, 27).

Overall, the integration of combining ability analysis with multi-trait evaluation provides a robust framework for identifying elite parents and promising hybrids. The results of this study offer valuable insights for designing efficient bottle gourd breeding programs tailored to exploit both additive and non-additive genetic effects under eastern Indian agro-climatic conditions.

Conclusion

The present study revealed that both additive and non-additive gene actions govern yield and quality traits in bottle gourd, with predominance of non-additive effects for major yield traits. BRBG 65 and BRBG 190 were identified as superior general combiners, while hybrids such as BRBG 65 × Punjab Komal and BRBG 51-2 × BRBG 190 exhibited promising specific combining ability and heterotic potential for yield improvement. However, the study was conducted under a location and molecular characterisation and multi-location validation of hybrids were not included. Therefore, further evaluation across diverse environments is necessary to confirm the stability, adaptability and commercial utility of the identified hybrids for bottle gourd improvement programs.

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Authors' contributions

RKS conceived and designed the experiment. AK participated in field experimentation, data collection and recording of observations. AB assisted in planning the experiment, statistical analysis and interpretation of results. RBR contributed to genetic analysis and manuscript improvement. PS assisted in data interpretation, manuscript editing and overall coordination of the study. All authors have read and approved the final manuscript.

Compliance with ethical standards

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

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used Perplexity and ChatGPT (OpenAI) to assist in literature searching, language refinement, grammatical editing and improving the overall presentation of the manuscript. All generated content was carefully reviewed, revised and validated by the authors, who take full responsibility for the accuracy, originality and integrity of the final submitted work.

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