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RESEARCH ARTICLE

# Combining ability analysis for fruit yield and related traits in Brinjal (*Solanum melongena* L.) using Line × Tester mating design

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## Abstract

Brinjal (*Solanum melongena* L.) is a significant vegetable crop, widely cultivated and consumed in almost every household across India. Enhancing fruit production per unit area requires a focus on key traits such as early maturity, enhanced plant vigor and increased fruit yield. Consequently, crop breeding programs emphasize the development and commercialization of brinjal hybrids tailored to regional needs. Effective crop improvement hinges on selecting suitable parental lines and employing precise crossing techniques to generate hybrids with desirable agronomic traits. The present study was conducted to assess the combining ability for fruit yield and related traits in brinjal. The experiment was carried out during the *Kharif* season of 2023 and the summer season of 2024 at the Vegetable Research Centre, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India. A randomized block design (RBD) with three replications was utilized. The study involved 30 hybrid combinations derived from 13 brinjal genotypes, employing a line × tester mating design with 10 lines and 3 testers. Results indicated that among the parental genotypes, PBGL-5 (88.11), PBGL-7 (85.02) and Swarna Abhinav (67.80) demonstrated high general combining ability (GCA) for fruit yield and related traits. Among the hybrid combinations, Pusa Kaushal × Pant Samrat (153.16), Pusa Ankur × Kashi Uttam (126.37) and PBGL-5 × Pant Rituraj (116.77) exhibited superior specific combining ability (SCA) effects. These results highlight the potential of the identified parents and hybrids as promising genetic resources for future breeding programs aimed at hybrid development and yield enhancement. In conclusion, the identified genotypes and crosses with favorable GCA and SCA effects can serve as valuable candidates for breeding programs to develop high-yielding, region-specific brinjal hybrids. This study underscores the importance of systematic parental selection and hybrid evaluation in advancing brinjal crop improvement initiatives.

## Keywords

brinjal; GCA; SCA; testers; yield

## Introduction

Brinjal (*Solanum melongena* L.), a significant member of the Solanaceae family, is a vegetable crop originating from the Indo-Burma region, which harbors considerable genetic diversity along with its wild relatives. Commonly referred to as eggplant, aubergine, or Guinea squash, brinjal is believed to have originated in the Old World before disseminating to the New World (1). Its cultivation predominantly occurs during the summer and rainy seasons (2), with the crop exhibiting optimal growth under conditions of high rainfall and warm temperatures. These environmental adaptations make brinjal one of the few vegetable crops capable of achieving substantial yields in hot and humid climates (2, 3). Brinjal holds considerable dietary and cultural importance in India, where it constitutes a staple ingredient in various cuisines across diverse socio-economic strata (4). Morphologically, the plant exhibits a semi-spreading growth habit with an erect stature. Although inherently perennial, brinjal is predominantly cultivated as an herbaceous annual crop (5, 6). While the species is primarily self-pollinated, cross-pollination can occur at a rate of up to 20% under hot and humid conditions, facilitated by insect or wind activity. The crop's photo-insensitivity allows for biannual cultivation, a trait that significantly accelerates breeding and crop improvement programs. Its fruit, botanically classified as a berry, is borne either singly or in clusters on the plant (1, 5). Widely cultivated across India, with the exception of high-altitude regions (1, 4), brinjal demonstrates exceptional adaptability, enabling year-round cultivation under diverse agro -climatic conditions. The crop exhibits extensive morphological variability in its fruit, which ranges from round or egg-shaped to elongated, club-shaped forms. The color spectrum of brinjal fruits includes white, yellow, green and varying shades of purple to nearly black (5). The species is often termed the "king of vegetables," attributed to the distinctive crown-like calyx structure at the apex of its fruit. Brinjal finds extensive applications in culinary practices, including direct cooking, pickling and processing in dehydration industries (4).

In recent years, brinjal (eggplant) breeding programs have increasingly focused on the development of traits such as early bearing, enhanced yields and resistance to a range of biotic and abiotic stresses. The selection of appropriate parental lines, based on their combining ability, is a cornerstone of any effective breeding program (7). General combining ability (GCA) primarily captures additive or fixable genetic variance, whereas specific combining ability (SCA) reflects dominance or non-fixable genetic variance. A widely adopted approach in plant breeding for hybrid development is the line × tester mating design, which involves crossing 'l' lines with 't' testers. This approach generates full-sib and half-sib progeny, both of which, along with the parental lines, are subsequently evaluated under field conditions (8). Testers are specific genotypes employed to identify superior germplasm for hybrid development (9). The simplicity and utility of the line × tester design enable breeders to gain critical insights into the comparative performance of lines, thereby facilitating the selection of desirable traits. Findings from such analysis are instrumental in advancing breeding strategies aimed at improving agronomic traits, including yield. Furthermore, this approach enhances the understanding of genetic correlations, thereby supporting the identification of optimal hybrid combinations and elucidating the gene actions underlying these traits. Such advancements contribute not only to the refinement of brinjal breeding programs but also to broader insights into genetic interactions in plant breeding (8, 10). The success of breeding programs depends significantly on the identification and selection of favorable gene combinations in lines exhibiting high combining ability, coupled with the isolation of valuable germplasm. Certain lines demonstrate exceptional performance when crossed, producing progeny with superior agronomic traits, whereas others, despite showing potential, fail to yield desirable results. Consequently, the evaluation of both GCA and SCA provides critical insights into the genetic basis of trait inheritance and hybrid performance (7, 10). To devise an effective breeding strategy for accelerated crop improvement, it is imperative to comprehensively understand the gene actions governing the inheritance of economically significant quantitative traits. This understanding is vital for the development of high-yielding and resilient brinjal varieties. Although considerable progress has been made in eggplant cultivation, detailed studies on the combining ability of specific parental lines, particularly concerning yield-related traits, remain limited. An in-depth investigation of the genetic mechanisms influencing these traits is essential to refine hybrid breeding methodologies.

Addressing these gaps, the present study aims to evaluate both GCA and SCA to determine the predominant modes of gene action influencing key growth and yield traits in brinjal. To strengthen research in this domain, it is crucial to define research gaps clearly, formulate precise hypotheses and establish specific objectives. The genetic understanding gained from this study, particularly concerning traits in parental lines and their hybrids, along with the identification of superior combiners, will serve as a valuable resource for breeders in future crossing programs. Consequently, this research focuses on estimating GCA and SCA for fruit yield and its components in brinjal, thereby contributing to the development of high-performing hybrids.

## Materials and Methods

The present study was conducted at the Vegetable Research Centre, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India, with the aim of evaluating general and specific combining ability for fruit yield and its associated traits among brinjal (*Solanum melongena* L.) genotypes. The experiment spanned two distinct growing seasons: *Kharif* 2023 and summer 2024. A line × tester mating design was employed to develop 30 cross combinations, utilizing 10 lines and 3 testers, replicated three times in a Randomized Block Design (RBD). The genetic material included 13 promising brinjal genotypes sourced from multiple institutions. Eight genotypes were obtained from Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, namely: PBGL-7, PBGL-5, PB-114, PB-112, PBPL-6, Pant Samrat, Pant Rituraj and PBWR-1. Three genotypes were acquired from the Indian Agricultural Research Institute (IARI), New Delhi: Pusa Ankur, Pusa Kaushal and Pusa Anupam. Additionally, Swarna Abhinav and Kashi Uttam were sourced from the ICAR-Research Complex for Eastern Region, Patna, Bihar and the Indian Institute of Vegetable Research, Varanasi, Uttar Pradesh, respectively. The testers selected; Pant Rituraj, Pant Samrat and Kashi Uttam were chosen based on their broad genetic base and desirable agronomic traits. These genotypes are well-known for their strong combining ability, particularly for yield-related traits and have demonstrated superior hybrid performance in various breeding programs.

The experimental field was characterized by moderately fertile sandy loam soil, with a pH range of 6.0 to 6.5 and fine-to-medium texture. The cropping seasons encompassed diverse climatic conditions. During the summer season (April–June), temperatures ranged from 26.2°C to 33.4°C, whereas the winter season (October-February) experienced temperatures between 18.8°C and 10.3°C. Parental seeds were initially raised on nursery beds measuring 1 m in width and 3 m in length. The crossing program, conducted between July and November 2022, was initiated at the flowering stage and continued until sufficient fruit set was achieved, resulting in the development of 30 single-cross hybrids. During the evaluation, nursery beds were used for seed sowing in both growing seasons. To mitigate significant biotic stresses, including infestations by shoot and fruit borers and Phomopsis blight, timely applications of Chlorantraniliprole 18.5% W/W (1.2%) and Captan (2%) were administered weekly. Nutrient management adhered to recommended doses of nitrogen, phosphorus and potassium (100:50:50 kg/ha), applied through urea, single super phosphate and muriate of potash. Weed management was performed manually to maintain weed-free conditions and irrigation was scheduled every 2-3 days based on soil moisture status and environmental conditions to support optimal plant growth. This rigorous experimental approach ensured reliable assessment of the genetic potential of the parental lines and hybrids, facilitating the identification of promising genotypes for future breeding programs.

### *Observations recorded*

Several biometric observations *viz.,* plant height, days to 50% flowering, days to first fruit picking, number of primary branches, leaf area, number of flowers per cluster, number of fruits per cluster, length of calyx, length of pedicel, fruit length, fruit diameter, average fruit weight and yield, were recorded from each replication using five randomly selected plants at different growth stages. Plant height was measured from the base of the soil to the plant's tip using a meter scale. Days to 50% flowering was determined through morphological observation, while days to first fruit picking were recorded by counting the days after transplanting. The number of primary branches, number of flowers per plant and number of fruits per plant were counted based on physical observation. Leaf area values were recorded using leaf area meter. The length of calyx, pedicel and fruits were measured by using centimeter scale. Fruit diameter values were recorded by vernier caliper. The average fruit weight and yield were measured using weighing balance.

### *Statistical analysis*

The data was recorded and analyzed using TNAUSTAT software (11). The dataset was subjected to line × tester analysis to obtain information about general combining ability and special combining ability, as described by (11).

## Results

### *Analysis of Variance*

The analysis of variance (ANOVA) for the mean sum of squares indicated that most traits exhibited significant effects across multiple factors, including season, crosses, line effects, tester effects, line × tester interactions, season × cross interactions, season × line interactions and season × line × tester interactions. Notably, the mean sum of squares for season and line × tester interactions was significant for all thirteen yield-related traits and their components. Among these traits, six showed significant mean sum of squares due to cross and tester effects. Conversely, the mean sum of squares for line effects and season × line interactions was significant for two traits. Furthermore, ten traits demonstrated significant effects for the season × cross interaction, while nine traits exhibited significant influences from the season × line × tester interaction (Table 1).

**Table 1.** Analysis of variance for combining ability in various characters of brinjal across pooled data from kharif 2023 and summer 2024 seasons

| Source of variation | Mean sum of squares | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Replication | Seasons | Crosses | Line effect | Tester effect | Line × Tester effect | Season × Crosses | Season × Line effect | Season × Tester effect | S × L × T effect | Error |
| **Degrees of freedom** | 2 | 1 | 29 | 9 | 2 | 18 | 29 | 9 | 2 | 18 | 116 |
| Plant Height (cm) | 1.20 | 383.80** | 1106.14** | 1564.64 | 2017.45 | 775.63** | 39.79** | 39.51 | 22.98 | 41.80** | 3.58 |
| Days to 50% flowering | 3.07 | 8296.02** | 106.43** | 98.18 | 158.67 | 104.76** | 7.59** | 10.82 | 11.71 | 5.51** | 1.66 |
| Days to first fruit picking | 24.77 | 33347.22** | 230.09** | 95.60 | 1283.17** | 180.33** | 111.89** | 154.01** | 324.21 | 67.24** | 8.88 |
| Number of primary branches | 0.06 | 2.15** | 12.44** | 9.84 | 11.43 | 13.85** | 2.74** | 3.04 | 5.11 | 2.33** | 0.11 |
| Leaf area ($cm^2$) | 119.51 | 15.75 | 19278.53** | 33660.53* | 6685.56 | 13486.75* | 778.69 | 1576.32* | 111.01 | 454.06 | 877.24 |
| Number of flowers per cluster | 0.34 | 0.11 | 1.76** | 1.74 | 6.82* | 1.21** | 0.07 | 0.06 | 0.04 | 0.08 | 0.13 |
| Number of fruits per cluster | 0.003 | 0.03 | 2.14** | 2.31 | 3.75 | 1.87** | 0.04** | 0.04 | 0.00 | 0.04** | 0.02 |
| Length of calyx (cm | 0.002 | 0.002 | 0.90** | 0.79 | 1.37 | 0.91** | 0.07* | 0.09 | 0.02 | 0.06 | 0.04 |
| Length of pedicel (cm) | 0.02 | 0.04 | 2.11** | 2.52 | 8.83** | 1.16** | 0.19** | 0.14 | 0.15 | 0.21** | 0.08 |
| Fruit length (cm) | 0.11 | 0.62 | 51.47** | 49.60 | 267.45** | 28.41** | 1.65** | 0.96 | 0.48 | 2.12** | 0.32 |
| Fruit diameter (cm) | 0.17 | 0.09 | 10.13** | 15.88** | 42.30** | 3.69** | 0.24** | 0.24 | 0.12 | 0.25* | 0.13 |
| Average fruit weight (g) | 1.28 | 4843.41** | 7462.90** | 7691.78 | 22728.66** | 5652.27** | 948.28** | 797.64 | 1635.16 | 947.29** | 11.33 |
| Yield (q/ha) | 25.03 | 327953.97** | 64624.91** | 67098.75 | 81087.27 | 61558.83** | 948.26 | 797.72 | 1635.29 | 947.18 | 639.86 |

*, ** at 5% and 1% level of significance, respectively

## Mean Performance

The average performance of the thirteen parental lines and their thirty $F_1$ hybrid cross combinations across thirteen distinct growth and yield traits is summarized in Table 2.

## Estimation of Combining Ability

The analysis of combining ability offers critical insights into the genetic mechanisms underlying trait expression, facilitating the identification of optimal breeding strategies for improving

**Table 2.** Mean performance of $F_1$ and parents during *Kharif* season 2023 for growth and yield traits of brinjal

| Genotypes | Plant Height (cm) | Days to 50% flowering | Days to first fruit picking | Number of primary branches | Leaf area (cm²) | Number of flowers per cluster | Number of fruits per cluster | Length of calyx (cm) | Length of pedicel (cm) | Fruit length (cm) | Fruit diameter (cm) | Average fruit weight (g) | Yield (q/ha) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PBGL-7 × Pant Rituraj | 79.01 | 68.67 | 104.00 | 8.72 | 195.29 | 3.63 | 1.91 | 3.06 | 4.38 | 10.92 | 6.12 | 83.60 | 413.34 |
| PBGL-7 × Pant Samrat | 105.49 | 71.67 | 102.00 | 12.60 | 319.91 | 3.70 | 1.99 | 3.84 | 5.02 | 16.01 | 3.59 | 88.03 | 445.84 |
| PBGL-7 × Kashi Uttam | 64.66 | 79.33 | 115.33 | 11.20 | 186.32 | 2.73 | 1.98 | 3.66 | 4.49 | 10.54 | 5.23 | 104.27 | 552.56 |
| PBGL-5 × Pant Rituraj | 80.56 | 68.00 | 106.67 | 10.39 | 326.73 | 4.28 | 3.52 | 3.45 | 4.41 | 14.15 | 4.55 | 138.13 | 571.14 |
| PBGL-5 × Pant Samrat | 109.53 | 71.67 | 104.00 | 11.00 | 253.82 | 3.45 | 2.46 | 4.18 | 5.07 | 20.32 | 3.41 | 74.20 | 451.26 |
| PBGL-5 × Kashi Uttam | 77.20 | 74.33 | 106.67 | 10.17 | 154.85 | 2.33 | 2.20 | 3.58 | 4.96 | 13.65 | 5.15 | 119.60 | 408.80 |
| PB-114 × Pant Rituraj | 72.99 | 74.00 | 111.33 | 7.77 | 180.31 | 3.17 | 2.23 | 2.91 | 4.54 | 14.01 | 4.63 | 112.53 | 269.07 |
| PB-114 × Pant Samrat | 64.08 | 74.67 | 116.67 | 8.43 | 185.70 | 3.19 | 1.59 | 3.92 | 6.73 | 16.37 | 3.57 | 87.73 | 283.56 |
| PB-114 × Kashi Uttam | 53.17 | 82.67 | 115.00 | 10.30 | 175.23 | 2.42 | 1.23 | 4.03 | 5.44 | 9.53 | 4.92 | 100.00 | 393.11 |
| PB-112 × Pant Rituraj | 77.24 | 79.67 | 115.00 | 8.37 | 187.01 | 3.87 | 1.73 | 3.65 | 3.64 | 13.88 | 5.03 | 85.97 | 266.00 |
| PB-112 × Pant Samrat | 100.46 | 70.00 | 113.00 | 10.00 | 238.07 | 3.73 | 2.49 | 3.38 | 5.12 | 17.40 | 4.31 | 152.67 | 434.10 |
| PB-112 × Kashi Uttam | 73.73 | 78.00 | 115.33 | 9.47 | 179.62 | 3.03 | 3.00 | 3.85 | 4.43 | 12.37 | 7.52 | 136.33 | 286.58 |
| PBPL-6 × Pant Rituraj | 67.50 | 68.33 | 120.33 | 9.80 | 174.97 | 2.73 | 1.45 | 3.80 | 5.40 | 16.09 | 5.68 | 140.93 | 377.18 |
| PBPL-6 × Pant Samrat | 60.16 | 75.67 | 106.00 | 10.72 | 220.03 | 3.17 | 2.60 | 3.68 | 5.67 | 14.24 | 6.12 | 72.53 | 234.72 |
| PBPL-6 × Kashi Uttam | 58.43 | 77.67 | 123.33 | 11.10 | 167.30 | 3.00 | 1.57 | 3.80 | 4.15 | 13.56 | 5.36 | 154.10 | 369.19 |
| Pusa Ankur × Pant Rituraj | 79.63 | 71.67 | 107.33 | 10.17 | 169.25 | 3.15 | 1.85 | 3.85 | 3.71 | 16.12 | 3.85 | 109.47 | 340.21 |
| Pusa Ankur × Pant Samrat | 84.25 | 80.67 | 112.33 | 10.38 | 272.42 | 3.00 | 2.44 | 3.03 | 4.02 | 17.50 | 3.32 | 91.60 | 233.07 |
| Pusa Ankur × Kashi Uttam | 86.25 | 73.33 | 105.33 | 11.23 | 335.85 | 2.90 | 1.53 | 3.82 | 4.73 | 12.68 | 5.00 | 177.17 | 583.98 |
| Swarna Abhinav × Pant Rituraj | 61.97 | 67.33 | 106.00 | 11.92 | 375.29 | 4.38 | 3.62 | 2.83 | 3.69 | 15.11 | 5.63 | 179.20 | 518.11 |
| Swarna Abhinav × Pant Samrat | 99.67 | 77.33 | 128.00 | 6.57 | 290.97 | 3.08 | 2.03 | 3.14 | 4.89 | 14.40 | 5.29 | 107.20 | 260.67 |
| Swarna Abhinav × Kashi Uttam | 100.34 | 67.67 | 104.00 | 12.08 | 356.81 | 3.80 | 1.47 | 3.86 | 4.83 | 12.20 | 6.00 | 134.60 | 594.73 |
| Pusa Kaushal × Pant Rituraj | 64.27 | 70.67 | 107.67 | 10.28 | 222.99 | 4.32 | 2.67 | 4.02 | 5.27 | 17.08 | 5.74 | 131.33 | 325.24 |
| Pusa Kaushal × Pant Samrat | 85.74 | 69.33 | 108.33 | 9.30 | 179.20 | 3.53 | 1.43 | 3.85 | 4.85 | 14.63 | 3.92 | 117.07 | 532.55 |
| Pusa Kaushal × Kashi Uttam | 67.45 | 75.33 | 114.00 | 9.50 | 225.23 | 2.33 | 1.43 | 3.80 | 4.56 | 9.69 | 7.67 | 183.00 | 339.73 |
| Pusa Anupama × Pant Rituraj | 73.56 | 77.00 | 107.33 | 10.46 | 205.41 | 3.07 | 1.67 | 3.90 | 4.38 | 15.08 | 4.87 | 136.54 | 290.22 |
| Pusa Anupama × Pant Samrat | 50.21 | 76.33 | 128.00 | 7.59 | 182.59 | 2.88 | 2.17 | 3.96 | 4.50 | 14.43 | 4.38 | 86.73 | 374.62 |
| Pusa Anupama × Kashi Uttam | 69.42 | 74.67 | 114.33 | 6.87 | 199.80 | 3.65 | 1.53 | 3.54 | 3.93 | 7.50 | 5.40 | 221.00 | 346.58 |
| PBWR-1 × Pant Rituraj | 73.03 | 73.33 | 104.00 | 9.69 | 158.96 | 3.94 | 1.41 | 3.39 | 4.44 | 9.37 | 6.85 | 153.60 | 280.10 |
| PBWR-1 × Pant Samrat | 66.13 | 68.67 | 114.33 | 11.57 | 196.58 | 3.60 | 1.57 | 3.34 | 4.62 | 9.91 | 6.07 | 157.73 | 379.66 |
| PBWR-1 × Kashi Uttam | 73.33 | 76.67 | 112.00 | 11.97 | 155.55 | 3.12 | 1.27 | 3.61 | 4.86 | 11.33 | 9.19 | 162.80 | 488.74 |
| PBGL-7 | 82.08 | 82.33 | 128.00 | 9.23 | 378.30 | 3.20 | 2.80 | 3.29 | 5.70 | 14.38 | 2.95 | 69.55 | 179.32 |
| PBGL-5 | 102.63 | 80.00 | 127.67 | 11.06 | 240.99 | 3.13 | 2.89 | 3.49 | 5.06 | 16.17 | 3.61 | 68.13 | 281.99 |
| PB-114 | 63.21 | 88.67 | 128.33 | 6.52 | 265.74 | 2.20 | 2.10 | 2.76 | 4.43 | 16.13 | 2.81 | 66.30 | 160.78 |
| PB-112 | 113.76 | 81.00 | 104.33 | 9.42 | 188.60 | 3.17 | 2.47 | 3.01 | 5.37 | 14.27 | 3.90 | 75.47 | 299.10 |
| PBPL-6 | 70.52 | 77.00 | 118.00 | 9.28 | 188.99 | 3.03 | 1.53 | 3.58 | 4.67 | 14.56 | 4.71 | 67.40 | 280.84 |
| Pusa Ankur | 85.80 | 75.00 | 107.67 | 10.27 | 189.15 | 3.33 | 1.37 | 3.19 | 5.93 | 13.27 | 4.30 | 67.73 | 361.71 |
| Swarna Abhinav | 114.22 | 70.67 | 108.33 | 11.65 | 378.89 | 3.47 | 3.02 | 3.88 | 5.21 | 15.61 | 5.21 | 92.13 | 482.64 |
| Pusa Kaushal | 75.28 | 76.33 | 111.67 | 9.42 | 164.78 | 2.27 | 2.21 | 3.66 | 6.04 | 15.58 | 5.97 | 115.93 | 335.56 |
| Pusa Anupama | 63.40 | 78.67 | 115.00 | 9.38 | 163.79 | 3.33 | 1.39 | 3.42 | 5.39 | 12.43 | 5.47 | 101.86 | 234.52 |
| PBWR-1 | 93.63 | 81.33 | 128.00 | 9.74 | 151.84 | 3.40 | 1.36 | 2.79 | 4.56 | 8.13 | 8.59 | 78.47 | 270.99 |
| PR | 95.48 | 77.67 | 106.67 | 9.03 | 221.53 | 1.28 | 1.16 | 3.87 | 4.83 | 8.33 | 8.40 | 110.00 | 326.44 |
| PS | 106.60 | 84.67 | 107.67 | 6.70 | 239.55 | 3.22 | 2.22 | 3.54 | 5.85 | 14.22 | 3.55 | 68.67 | 267.12 |
| KU | 69.28 | 73.00 | 104.33 | 9.70 | 223.34 | 1.54 | 1.45 | 3.42 | 5.23 | 9.40 | 9.58 | 112.14 | 371.23 |
| **General Mean** | **79.43** | **75.36** | **112.64** | **9.79** | **224.83** | **3.16** | **2.00** | **3.55** | **4.86** | **13.55** | **5.29** | **113.80** | **360.39** |
| **C.D.** | 3.37 | 2.25 | 5.62 | 0.65 | 17.76 | 0.60 | 0.27 | 0.36 | 0.57 | 0.97 | 0.50 | 5.00 | 48.65 |
| **SE(m)** | 1.20 | 0.80 | 2.00 | 0.23 | 6.31 | 0.21 | 0.10 | 0.13 | 0.20 | 0.34 | 0.18 | 1.78 | 17.27 |
| **SE(d)** | 1.69 | 1.13 | 2.82 | 0.33 | 8.92 | 0.30 | 0.13 | 0.18 | 0.29 | 0.49 | 0.25 | 2.51 | 24.42 |

heritable characteristics. This section discusses the GCA effects of the experimental lines and testers, as well as the SCA effects of the hybrids, for the thirteen evaluated traits. These findings are detailed below, providing a comprehensive understanding of the genetic contributions to trait performance.

### *Estimation of General Combining Ability (GCA)*

The pooled data on the range and GCA effects for various growth and yield parameters are summarized in Table 3. The results demonstrate significant variation in GCA effects across traits. The GCA effect for plant height ranged from -12.38 to 11.29, with six positive values. Among the lines, PBGL-5 exhibited the highest positive GCA effect (11.29), followed by Swarna Abhinav (10.81) and PBGL-7 (7.30). Conversely, PBPL-6 recorded the lowest GCA effect (-12.38). Among the testers, Pant Samrat had the highest GCA effect (6.65), while Kashi Uttam displayed the lowest (-4.03). The estimates of GCA effects for the number of primary branches ranged from -1.17 to 0.87, with eight positive values. PBWR-1 showed the maximum positive GCA effect (0.87), followed by PBGL-5 (0.79), whereas PB-114 recorded the lowest (-1.17). For the testers, Kashi Uttam exhibited the highest GCA effect (0.35), while Pant Rituraj showed the lowest (-0.49). The GCA effect for days to 50% flowering ranged from -3.91 to 3.76, with five negative values. Among the lines, Swarna Abhinav (-3.91) and Pusa Kaushal (-2.69) recorded the lowest GCA effects, while PB-114 displayed the highest (3.76). For the testers, Pant Rituraj had the lowest value (-1.59) and Kashi Uttam recorded the highest (1.66). The GCA effect for days to first fruit picking varied from -5.26 to 3.42, with four negative values. Among the lines, Pusa Ankur (-3.09) exhibited the lowest GCA effect, followed by PBGL-5 (-2.76) and Pusa Kaushal (-1.59), whereas Pusa Anupama showed the highest (4.86). For the testers, Pant Rituraj recorded the lowest value (-5.26) and Pant Samrat exhibited the highest (3.42).

The GCA effect for leaf area ranged widely, from -38.96 to 103.66, with four positive values. Swarna Abhinav exhibited the highest GCA effect (103.66), followed by Pusa Ankur (31.58). PB-114 showed the lowest value (-38.96). Among the testers, Pant Samrat had the highest GCA effect (11.13), while Kashi Uttam recorded the lowest (-9.87). The GCA effect for the number of flowers per cluster ranged from -0.43 to 0.56, with three positive values. Among the lines, Swarna Abhinav (0.56) exhibited the highest GCA effect, followed by PB-112 (0.30). PB-114 recorded the lowest value (-0.43). For the testers, Pant Rituraj (0.32) and Kashi Uttam (-0.35) exhibited the highest and lowest values, respectively. The GCA effect for the number of fruits per cluster ranged from -0.55 to 0.63, with five positive values. Among the lines, PBGL-5 showed the highest GCA effect (0.63), followed by PB-112 (0.44). PBWR-1 exhibited the lowest value (-0.55). For the testers, Pant Rituraj (0.19) and Kashi Uttam (-0.28) showed the highest and lowest values, respectively. The GCA effect for calyx length ranged from -0.31 to 0.33, with four positive values. Pusa Kaushal showed the maximum GCA effect (0.33), followed by Pusa Anupama (0.24) and PBPL-6 (0.23). Swarna Abhinav recorded the lowest value (-0.31). For the testers, Kashi Uttam (0.14) and Pant Samrat (-0.16) showed the highest and lowest values, respectively. The GCA effect for pedicel length ranged from -0.42 to 0.85, with four positive values. PB-114 displayed the highest GCA effect (0.56), followed by PBPL-6 (0.30), while Pusa Ankur recorded the lowest (-0.42). For the testers, Pant Samrat (0.41) and Pant Rituraj (-0.34) exhibited the highest and lowest values, respectively. The GCA effect for fruit length ranged from -3.61 to 2.53, with seven positive values. PBGL-5 exhibited the maximum GCA effect (2.53), followed by Pusa Ankur (1.44) and PBPL-6 (0.82). PBWR-1 showed the lowest value (-3.61). Among the testers, Pant Samrat (1.75) and Kashi Uttam (-2.34) recorded the highest and lowest values, respectively.

The GCA effect for fruit diameter ranged from -1.23 to 2.09, with six positive values. PBWR-1 exhibited the highest GCA effect (2.09), followed by Pusa Kaushal (0.39). Pusa Ankur recorded the lowest value (-1.23). Among the testers, Kashi Uttam (0.85) and Pant Samrat (-0.83) showed the highest and lowest values, respectively. The GCA effect for average fruit weight ranged from -32.09 to 25.98, with seven positive values.

**Table 3.** The GCA of parents for plant growth and yield traits of brinjal

| Treatments | Plant Height (cm) | Days to 50% flowering | Days to first fruit picking | Number of primary branches | Leaf area (cm²) | Number of flowers per cluster | Number of fruits per cluster | Length of calyx (cm) | Length of pedicel (cm) | Fruit length (cm) | Fruit diameter (cm) | Average fruit weight (g) | Yield (q/ha) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Lines** | | | | | | | | | | | | | |
| PBGL-7 | 7.3** | -0.3 | -0.09 | 0.48** | 6.72 | 0.01 | 0.04 | -0.20** | -0.07 | -0.77** | -0.44** | -32.09** | 85.02** |
| PBGL-5 | 11.29** | -0.86** | -2.76** | 0.79** | 17.16* | 0.03 | 0.63** | 0.01 | 0.17** | 2.53** | -0.63** | -16.81** | 88.11** |
| PB-114 | -10.44** | 3.76** | 0.08 | -1.17** | -38.96** | -0.43** | -0.28** | -0.02 | 0.85** | -0.32* | -0.87** | -24.23** | -70.57** |
| PB-112 | 5.61** | 2.64** | -0.2 | -0.88** | -10.86 | 0.3** | 0.44** | -0.04 | -0.24** | 0.68** | 0.38** | 4.11** | -53.5** |
| PBPL-6 | -12.38** | -0.19 | 0.63 | 0.25** | -27.95** | -0.34** | -0.12** | 0.23** | 0.30** | 0.82** | 0.34** | 0.53 | -56.46** |
| Pusa Ankur | 6.68** | 1.37** | -3.09** | 0.26** | 31.58** | -0.28** | -0.07* | -0.08 | -0.42** | 1.44** | -1.23** | -12.81** | -14.63* |
| Swarna Abhinav | 10.81** | -3.91** | 0.13 | -0.02 | 103.66** | 0.56** | 0.29** | -0.31** | -0.17** | 0.06 | 0.36** | 11.79** | 67.8** |
| Pusa Kaushal | -3.31** | -2.69** | -1.59* | 0.36** | -19.11** | 0.15 | -0.13** | 0.33** | 0.00 | 0.33* | 0.39** | 23.15** | 17.02** |
| Pusa Anupama | -10.45** | 1.26** | 4.86** | -0.94** | -27.26** | -0.18 | -0.25** | 0.24** | -0.38** | -1.16** | -0.4** | 25.98** | -46.47** |
| PBWR-1 | -5.1** | -1.08** | 2.02** | 0.87** | -34.97** | 0.19 | -0.55** | -0.16** | -0.03 | -3.61** | 2.09** | 20.39** | -16.32** |
| SE (gi) | 0.38 | 0.30 | 0.70 | 0.06 | 6.72 | 0.10 | 0.02 | 0.04 | 0.06 | 0.12 | 0.08 | 0.81 | 5.87 |
| **Testers** | | | | | | | | | | | | | |
| Pant Rituraj | -2.62** | -1.59** | -5.26** | -0.49** | -1.27 | 0.32** | 0.19** | -0.16** | -0.34** | 0.59** | -0.02 | 4.59** | -18.98** |
| Pant Samrat | 6.65** | -0.07 | 3.42** | 0.14** | 11.13** | 0.03 | 0.10** | 0.02 | 0.41** | 1.75** | -0.83** | -21.35** | -23.39** |
| Kashi Uttam | -4.03** | 1.66** | 1.84** | 0.35** | -9.87** | -0.35** | -0.28** | 0.14** | -0.07* | -2.34** | 0.85** | 16.76** | 42.37** |
| SE (gj) | 0.21 | 0.16 | 0.38 | 0.03 | 3.68 | 0.05 | 0.01 | 0.02 | 0.03 | 0.06 | 0.04 | 0.44 | 3.21 |

*, ** at 5% and 1% level of significance, respectively

Pusa Anupama exhibited the highest GCA effect (25.98), followed by Pusa Kaushal (23.15) and PBWR-1 (20.39). PBGL-7 recorded the lowest value (-32.09). Among the testers, Kashi Uttam (16.76) and Pant Samrat (-21.35) exhibited the highest and lowest values, respectively. The GCA effect for fruit yield ranged from -70.57 to 88.11, with five positive values. Among the lines, PBGL-5 exhibited the highest GCA effect (88.11), followed by PBGL-7 (85.02) and Swarna Abhinav (67.80). PB-114 recorded the lowest value (-70.57). For the testers, Kashi Uttam (42.37) and Pant Samrat (-23.39) exhibited the highest and lowest values, respectively. This comprehensive evaluation highlights significant variation in GCA effects across different growth and yield parameters, suggesting a diverse genetic potential among the lines and testers for breeding programs.

### *Estimation of specific combining ability (SCA)*

The SCA results for various traits provide a critical framework for identifying superior cross combinations, including optimal lines and testers, based on their performance across different parameters. A summary of the pooled data, encompassing the range and impact of SCA estimates for growth and yield traits, is presented in Table 4. For plant height, significant SCA estimates were observed in 26 crosses over two years, with 13 displaying positive values. The top-performing crosses included Swarna Abhinav × Kashi Uttam (14.31), PB-114 × Pant Rituraj (11.26), PBGL-5 × Pant Samrat (10.69), PB-112 × Pant Samrat (8.53) and Pusa Anupama × Pant Rituraj (7.57). Regarding the number of primary branches, 27 crosses exhibited significant SCA estimates ranging from -2.02 to 2.72, with 14 displaying positive values. The highest positive SCA effect was recorded in Pusa Anupama × Pant Rituraj (2.72), followed by PBGL-7 × Pant Samrat (2.20), Swarna Abhinav × Pant Rituraj (1.58), PBWR-1 × Pant Samrat and PBWR-1 × Kashi Uttam (1.01). For days to 50% flowering, significant SCA estimates were recorded in 22 crosses, of which 13 showed positive effects. The leading combinations included Swarna Abhinav × Kashi Uttam (-6.11), PB-112 × Pant Samrat (-4.59), PBWR-1 × Pant Samrat (-4.21), Pusa Ankur × Kashi Uttam (-3.88) and PBPL-6 × Pant Rituraj (-3.74). In the case of days to first fruit picking, 19 crosses exhibited significant SCA estimates, ranging from -8.02 to 11.30, with 10 having negative values. The crosses with the lowest values were Swarna Abhinav × Pant Rituraj (-8.02), PBPL-6 × Pant Samrat (-6.37), PBGL-7 × Pant Samrat (-6.14), Pusa Anupama × Kashi Uttam (-4.17) and Pusa Anupama × Pant Rituraj (-4.07). For leaf area, significant estimates were observed in 13 crosses, with seven displaying positive values. The most prominent crosses were Pusa Ankur × Kashi Uttam (78.32), PBGL-5 × Pant Rituraj (71.53), PBGL-7 × Pant

**Table 4.** The SCA of crosses for plant growth and yield traits of brinjal

| Treatments | Plant Height (cm) | Days to 50% flowering | Days to first fruit picking | Number of primary branches | Leaf area (cm²) | Number of flowers per cluster | Number of fruits per cluster | Length of calyx (cm) | Length of pedicel (cm) | Fruit length (cm) | Fruit diameter (cm) | Average fruit weight (g) | Yield (q/ha) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PBGL-7 × Pant Rituraj | -1.67* | -1.97** | 0.87 | -1.97** | -31.18** | -0.07 | -0.25** | -0.18* | 0.05 | -2.19** | 0.87** | -12.35** | -37.66** |
| PBGL-7 × Pant Samrat | 14.79** | -1.65** | -6.14** | 2.2** | 63.07** | 0.24 | 0.09 | 0.32** | -0.13 | 2.45** | -0.28* | 16.71** | -2.05 |
| PBGL-7 × Kashi Uttam | -13.12** | 3.62** | 5.27** | -0.23* | -31.89** | -0.18 | 0.16** | -0.15 | 0.08 | -0.26 | -0.59** | -4.36** | 39.71** |
| PBGL-5 × Pant Rituraj | -2.52** | -0.91 | 4.71** | 0.41** | 71.53** | 0.59** | 0.5** | -0.12 | -0.04 | -2.33** | 0.05 | 26.62** | 116.77** |
| PBGL-5 × Pant Samrat | 10.69** | 0.07 | -3.31** | 0.8** | -0.94 | 0.15 | -0.3** | 0.48** | -0.02 | 2.62** | -0.08 | -11.46** | 1.22 |
| PBGL-5 × Kashi Uttam | -8.17** | 0.84 | -1.39 | -1.21** | -70.59** | -0.74** | -0.2** | -0.36** | 0.06 | -0.29 | 0.03 | -15.16** | -118** |
| PB-114 × Pant Rituraj | 11.26** | -0.19 | 0.54 | 0.17** | 2.40 | -0.09 | 0.46** | -0.55** | -0.62** | 0.05 | 0.44** | 6.25** | -28.8** |
| PB-114 × Pant Samrat | -5.99** | -2.71** | 0.19 | -0.57** | -4.86 | 0.12 | -0.22** | 0.27** | 0.68** | 1.37** | -0.12 | 10.01** | -7.27 |
| PB-114 × Kashi Uttam | -5.27** | 2.89** | -0.73 | 0.40** | 2.46 | -0.02 | -0.24** | 0.28** | -0.06 | -1.42** | -0.32* | -16.26** | 36.07** |
| PB-112 × Pant Rituraj | -1.09 | 4.09** | 2.65* | -0.91** | -19.76 | -0.13 | -0.83** | 0.21** | -0.27* | -1.56** | -0.77** | -26.54** | -26.84** |
| PB-112 × Pant Samrat | 8.53** | -4.59** | -1.87 | 0.29* | 37.82** | 0.08 | -0.09 | -0.35** | 0.13 | 0.41 | -0.51** | 35.4** | 114.97** |
| PB-112 × Kashi Uttam | -7.44** | 0.51 | -0.78 | 0.62** | -18.05 | 0.06 | 0.92** | 0.15 | 0.14 | 1.14** | 1.28** | -8.86** | -88.13** |
| PBPL-6 × Pant Rituraj | 6.89** | -3.74** | 2.15 | -0.63** | -6.20 | -0.52** | -0.61** | 0.16* | 0.56** | 1.92** | 0.07 | 7.87** | 63.18** |
| PBPL-6 × Pant Samrat | -6.98** | 0.91 | -6.37** | -0.01 | 16.44 | 0.09 | 0.62** | -0.14 | 0.11 | -2.02** | 1.26** | -30.68** | -70.95** |
| PBPL-6 × Kashi Uttam | 0.1 | 2.84** | 4.22** | 0.64** | -10.25 | 0.42* | -0.01 | -0.02 | -0.67** | 0.1 | -1.33** | 22.81** | 7.77 |
| Pusa Ankur × Pant Rituraj | -3.17** | -2.30** | -0.96 | -0.15 | -82.61** | -0.13 | -0.27** | 0.37** | -0.13 | 0.27 | -0.12 | -8.06** | -13.43 |
| Pusa Ankur × Pant Samrat | -5.22** | 6.18** | 3.69** | 0.31** | 4.29 | -0.08 | 0.4** | -0.64** | -0.35** | -0.27 | 0.13 | 3.22* | -112.94** |
| Pusa Ankur × Kashi Uttam | 8.39** | -3.88** | -2.73* | -0.16 | 78.32** | 0.2 | -0.13* | 0.27** | 0.47** | 0.01 | -0.01 | 4.84** | 126.37** |
| Swarna Abhinav × Pant Rituraj | -19.84** | -1.86** | -8.02** | 1.58** | 35.15** | 0.3 | 0.88** | -0.36** | -0.42** | 0.22 | -0.23 | 31.52** | 76.5** |
| Swarna Abhinav × Pant Samrat | 5.53** | 7.96** | 11.30** | -2.46** | -60.12** | -0.51** | -0.32** | -0.15 | 0.30** | -1.43** | 0.57** | -7.15** | -169.14** |
| Swarna Abhinav × Kashi Uttam | 14.31** | -6.11** | -3.28** | 0.89** | 24.97** | 0.21 | -0.55** | 0.51** | 0.11 | 1.21** | -0.34* | -24.37** | 92.64** |
| Pusa Kaushal × Pant | -4.59** | 2.26** | 3.04* | 0.80** | 13.19 | 0.48** | 0.67** | 0.25** | 0.50** | 2.9** | -0.03 | -10.34** | -48.23** |
| Pusa Kaushal × Pant | 4.68** | -2.76** | -3.31** | -0.52** | -38.74** | 0.2 | -0.55** | -0.06 | -0.15 | -1.10** | -1.1** | -8.99** | 153.16** |
| Pusa Kaushal × Kashi | -0.1 | 0.51 | 0.27 | -0.27* | 25.55* | -0.69** | -0.12* | -0.19* | -0.35** | -1.81** | 1.13** | 19.33** | -104.93** |
| Pusa Anupama × Pant | 7.57** | 2.14** | -4.07** | 2.72** | 8.67 | -0.41* | -0.34** | 0.13 | 0.34** | 2.36** | 0.09 | -19.33** | -31.12** |
| Pusa Anupama × Pant | -16.24** | 0.79 | 8.24** | -1.04** | -21.89 | -0.36* | 0.34** | 0.33** | -0.08 | -0.11 | 0.29* | -43.36** | 57.52** |
| Pusa Anupama × Kashi | 8.67** | -2.94** | -4.17** | -1.68** | 13.21 | 0.77** | 0.00 | -0.46** | -0.26* | -2.25** | -0.38** | 62.69** | -26.4* |
| PBWR-1 × Pant Rituraj | 7.16** | 2.48** | -0.91 | -2.02** | 8.81 | -0.03 | -0.20** | 0.09 | 0.02 | -1.64** | -0.37* | 4.36** | -70.37** |
| PBWR-1 × Pant Samrat | -9.79** | -4.21** | -2.42* | 1.01** | 4.92 | 0.06 | 0.04 | -0.06 | -0.50** | -1.93** | -0.15 | 36.3** | 35.49** |
| PBWR-1 × Kashi Uttam | 2.63** | 1.73** | 3.33** | 1.01** | -13.73 | -0.03 | 0.16** | -0.03 | 0.48** | 3.56** | 0.52** | -40.66** | 34.88** |
| **CD at 5%** | 1.87 | 1.48 | 3.42 | 0.31 | 32.60 | 0.49 | 0.14 | 0.22 | 0.31 | 0.60 | 0.39 | 3.93 | 28.48 |
| **CD at 1%** | 2.49 | 1.97 | 4.55 | 0.42 | 43.30 | 0.65 | 0.19 | 0.29 | 0.42 | 0.80 | 0.52 | 5.2 | 37.84 |

*, ** at 5% and 1% level of significance, respectively

Samrat (63.07), PB-112 × Pant Samrat (37.82) and Swarna Abhinav × Pant Rituraj (35.15). In terms of number of flowers per cluster, 10 crosses showed significant SCA estimates, with four displaying positive effects. These included Pusa Anupama × Kashi Uttam (0.77), PBGL-5 × Pant Rituraj (0.59), Pusa Kaushal × Pant Rituraj (0.48) and PBPL-6 × Kashi Uttam (0.42).

For number of fruits per cluster, 25 crosses exhibited significant SCA estimates, with 10 yielding positive values ranging from -0.83 to 0.92. The leading crosses were PB-112 × Kashi Uttam (0.92), Swarna Abhinav × Pant Rituraj (0.88), Pusa Kaushal × Pant Rituraj (0.67), PBPL-6 × Pant Samrat (0.62) and PBGL-5 × Pant Rituraj (0.50). In the case of calyx length, significant estimates were identified in 19 crosses, with 11 showing positive values. The most promising crosses were Swarna Abhinav × Kashi Uttam (0.51), PBGL-5 × Pant Samrat (0.48), Pusa Ankur × Pant Rituraj (0.37), Pusa Anupama × Pant Samrat (0.33) and PBGL-7 × Pant Samrat (0.32). For pedicel length, 15 crosses recorded significant estimates ranging from -0.67 to 0.68, with seven exhibiting positive values. The top performers included PB-114 × Pant Samrat (0.68), PBPL-6 × Pant Rituraj (0.56), Pusa Kaushal × Pant Rituraj (0.50), PBWR-1 × Kashi Uttam (0.48) and Pusa Ankur × Kashi Uttam (0.47). The results for fruit length revealed significant SCA estimates in 20 crosses, with nine showing positive values. The leading combinations were PBWR-1 × Kashi Uttam (3.56), Pusa Kaushal × Pant Rituraj (2.90), PBGL-5 × Pant Samrat (2.62), PBGL-7 × Pant Samrat (2.45) and Pusa Anupama × Pant Rituraj (2.36). For fruit diameter, significant values were observed in 18 crosses, with eight showing positive estimates. The top crosses were PB-112 × Kashi Uttam (1.28), PBPL-6 × Pant Samrat (1.26), Pusa Kaushal × Kashi Uttam (1.13), PBGL-7 × Pant Rituraj (0.87) and Swarna Abhinav × Pant Samrat (0.57). Regarding average fruit weight, 30 crosses exhibited significant SCA estimates, with 13 having positive values. The highest effects were observed in Pusa Anupama × Kashi Uttam (62.69), PBWR-1 × Pant Samrat (36.30), PB-112 × Pant Samrat (35.40), Swarna Abhinav × Pant Rituraj (31.52) and PBGL-5 × Pant Rituraj (26.62). Lastly, for fruit yield, significant estimates were recorded in 25 crosses, with 12 showing positive values ranging from -169.14 to 153.16. The highest yields were noted in Pusa Kaushal × Pant Samrat (153.16), Pusa Ankur × Kashi Uttam (126.37), PBGL-5 × Pant Rituraj (116.77), PB-112 × Pant Samrat (114.97) and Swarna Abhinav × Kashi Uttam (92.64). These findings underscore the potential of certain crosses in contributing to the improvement of key agronomic and yield-related traits through strategic breeding programs.

## Discussion

The genetic control of brinjal traits was evaluated through the analysis of GCA and SCA. The GCA analysis, which provides a measure of the additive genetic effects, serves as a valuable tool for identifying superior parental lines and testers with favorable genetic potential for various traits. The results revealed positive GCA effects for parents such as PBGL-5, Swarna Abhinav and PBGL-7, particularly for traits including plant height, number of primary branches, leaf area and fruit yield. These findings suggest a preponderance of additive gene action, making these parents promising candidates for the improvement of traits such as plant architecture, earliness and yield through recurrent selection (12-17). In contrast, traits such as plant height, early flowering and fruit yield exhibited significant non-additive gene action, although this effect was not pronounced for traits like pedicel length and leaf area. Specifically, crosses like Swarna Abhinav × Kashi Uttam and Pusa Kaushal × Pant Samrat demonstrated substantial hybrid vigor, indicating the potential for the development of high-yielding, early-maturing varieties. These observations underscore the importance of both GCA and SCA in the selection of parent materials and hybrid combinations for the production of superior brinjal hybrids (18-23). Breeding efforts in eggplant for traits such as plant height, number of primary branches, early flowering and yield depend heavily on the principles of GCA and SCA. The current study demonstrated that certain parental lines yielded progeny with increased plant height and branch numbers, which were associated with both desirable and undesirable alleles, as reflected in the GCA values. This insight is crucial for breeders to select parents that will enhance these traits in future generations, thereby improving overall plant growth and fruit yield. Additionally, high GCA values for traits such as days to 50% flowering and days to first fruit picking suggest that the selected parents possess genetic potential for early fruiting-an essential trait for marketability and yield (6, 17-19). Breeding parents with favorable GCA for early fruiting will likely improve market value through the production of early-harvested crops.

The GCA analysis for yield and related traits further highlighted parental lines that consistently produced high-yielding progeny, thereby contributing to the development of high-yielding cultivars. GCA remains a fundamental tool in breeding strategies aimed at enhancing crop productivity and plant health. These findings align with previous reports (13, 14, 15, 24, 25). SCA analysis revealed that certain cross combinations consistently yielded tall progeny with abundant branches, attributed to the specific genetic interactions between the parent lines. These findings provide crucial insights for breeders, offering a basis for the selection of promising hybrid combinations to enhance desirable traits in subsequent generations. The SCA estimates also revealed that some crosses resulted in early-fruiting progeny, which suggests that specific gene interactions favor early fruiting, a characteristic that significantly contributes to fruit production and overall productivity (18-23). Moreover, the SCA analysis of yield and related traits indicated variability in hybrid performance, with some crosses producing high-yielding genotypes and others yielding lower productivity, depending on the genetic combinations involved. These results highlight the potential of utilizing crosses with strong SCA to breed high-yielding hybrids, thus improving the economic viability for small-scale farmers. SCA is, therefore, indispensable for identifying superior parental combinations and developing cultivars that are well-suited for cultivation. These findings corroborate the results of similar studies (12, 13, 15, 24-26).

## Conclusion

The present study provides clear evidence that, among the parental genotypes, Swarna Abhinav and Pusa Kaushal were identified as the best general combiners. In terms of specific combining ability for earliness, the crosses Swarna Abhinav × Kashi Uttam and PB-112 × Pant Samrat demonstrated superior performance. For fruit yield, the parents PBGL-5, PBGL-7 and

Swarna Abhinav exhibited strong general combining ability, while the crosses Pusa Kaushal × Pant Samrat, Pusa Ankur × Kashi Uttam and PBGL-5 × Pant Rituraj were found to possess superior positive specific combining ability effects. These results underscore the significant potential of these parental lines and crosses for utilization in selection and future breeding programs, offering valuable genetic resources for the development of hybrids with enhanced vigor, early-bearing characteristics and high fruit yield. The outcomes of this study provide a foundation for future genetic improvements and hold substantial promise for advancing crop breeding strategies.

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## Authors' contributions

IS carried out the field trial, data analysis and drafting of the manuscript, DS advised and supervised the full research work critically, RKS helped in manuscript drafting and data analysis, SS assisted in manuscript drafting and editing, RRY assisted in manuscript editing and data analysis, UJ assisted in manuscript drafting, editing and final editing, ADK helped in manuscript editing and field trial, K helped in editing of manuscript and field trial, HK helped in field trial, NR assisted in field trial. All the 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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