**Assessment of combining ability and *per se* performance of CGMS based hybrids in Chilli (*Capsicum annuum L*.) through L**$×$**T design**

**ABSTRACT**

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| Exploitation of male sterility in Chilli offers an efficient and strategic approach to maximizing heterosis for hybrid development. **Aim**-The present research investigates combining ability, *per se* performance and gene action in chilli by using CGMS lines through L$×$T mating design **Location of study** -The present study was conducted at the Department of Vegetable Science, College of Agriculture, Kerala Agricultural University from May 2022 to November 2024. **Methodology** -Combining ability was assessed using a Line $× $Tester mating design involving twenty four crosses. Three male sterile lines and eight testers were used to generate twenty four F₁ hybrids. F₁ seeds, obtained from the male sterile lines, were subsequently grown for hybrid evaluation and combining ability analysis. The experiment was laid out in a Randomized Block Design (RBD) and conducted under a rain shelter structure.**Results -**Combining ability analysis serves as a fundamental and highly effective tool for identifying desirable parents in breeding programs. Variance due to GCA and SCA showed significant and non-significant effects across different traits. The CGMS lines AVPP0517 and AVPP9907 along with tester Ujwala, Anugraha, VI059382 and AVPP9703 showed significant GCA for yield and other component trait.Highest significantly positive SCA recorded in AVPP0516$ ×$ Anugraha (34.25) for fruits plant-1.These crosses are also exhibited desirable SCA and the highest *per se* performance for yield plant-1 with highest SCA in AVPP0516 $× $Anugraha (176.55) and AVPP0517 $×$ VI059382 (172.57). Among the lines, AVPP9907 exhibited positive GCA for plant height, whereas the cross AVPP0517 $×$ LC217 recorded the highest SCA for this trait. Three hybrids AVPP0516 $×$ Anugraha, AVPP0517 $×$ VI059382 and AVPP9907 $× $Ujjwala were identified as most promising based on combining ability studies and *per se* performance. **Conclusion** -The analysis of gene action revealed that non-additive gene action predominantly influenced the expression of most the traits. The inheritance pattern strongly emphasized the importance of a hybrid breeding strategy for enhancing specific traits in Chilli.  |

*Key words- CGMS lines, Combining ability, GCA, SCA, Gene action, per se performance*

1. INTRODUCTION

Chilli (*Capsicum annuum* L) holds a prestigious status as a valuable industrial spice crop and is often referred to as the wonder spice. Its significance extends beyond culinary applications to medicinal, pharmaceutical, and industrial uses, making it highly sought after worldwide. Chilli is a widely cultivated *Capsicum* species grown across tropical and subtropical regions. It is a dual-purpose export commodity, serving as both a spice and a vegetable (Herath et al., 2020). Southern Mexico is recognized as the primary centre of origin, while India is considered as the secondary centre of diversity for *Capsicum* (Thakur et al., 2019). Chilli cultivation has spread throughout India since its introduction by the Portuguese in the 15th century. Currently, the crop covers an area of 423,700 hectares, with a production and productivity of 4,588,700 MT and 10.8 MT/ha, respectively. In India, Andra Pradesh stands first in area, production and productivity. Kerala shares an area of 1.32000 MT/ha with a production of 4.25 MT and productivity of 3.21 MT/ha, respectively (India stat, 2024). Dry chilli is the second largest spice exported from India, after black pepper. It accounted for about 42% of the country's total spice exports in 2022 (FAO, 2022). Heterosis breeding has shown to be increased the yield of chilli by 30-35% (Dhaliwal et al., 2014). In India, the demand for F1 hybrids has been growing steadily due to their genetic uniformity, built in resistance, wider adaptability and higher yield potential (Lata et al., 2023). These hybrids offer farmer’s a promising opportunity with increased productivity, consistent fruit quality, and enhanced export potential, making them highly profitable for commercial cultivation. Any crop improvement commences with identification of parental genotypes from diverse population. Prediction of hybrids based on *per se* performance of parents may not always be reliable, as the desirable traits are not always reliably inherited by the hybrids (Kadambavanasundaram, 1980). Combining ability is a fundamental tool in crop improvement, enabling the evaluation of parent’s breeding potential or the best combiner that can be hybridized to take advantage of heterosis and fix desirable genes (Chadha *et al*., 2001). Furthermore, it facilitates the evaluation of inbreds based on their genetic value and aids in selecting the most suitable parents for hybridization in chilli. GCA and SCA are the two components in combining ability analysis. GCA determines the average performance of parents in a series of crosses and specific combining ability gives the relative performance of parents involved in crosses. Magnitude of significant GCA and SCA effects show the efficacy of improvement in particular traits through suitable breeding method. Understanding the relative significance of additive and non-additive gene action is crucial for plant breeders in designing an effective hybridization program (Dudley and Moll, 1969). Additionally, selecting parents based on their combining ability is essential to achieving enhanced heterotic effects. L$×$T analysis evaluates both general and specific combining ability variances, along with their effects and genetic variance components, such as dominance (H) and additive (D) components, across a large number of germplasms, while minimizing the number of crosses required. Compared to full and half diallel methods, in this genetic analysis is more efficient in terms of space, resources, and time. The tester should be chosen strategically to provide the most comprehensive insights into the genetic performance of lines upon hybridization, even under varying environmental conditions, thereby ensuring broader adaptability (Manjunath et al., 2025). The hectic emasculation process poses a significant challenge in developing heterotic hybrids in chilli. In order to address this, integration of CGMS system has an immense potential for developing hybrids in Chilli (Prasad et al., 2022). In this context the study aims to analyse combining ability, *per se* performance and gene action in chilli by using CGMS lines through L$× $T design (Kempthorne, 1958).

2. material and methods

The field experiment was conducted at the Department of Vegetable Science, Kerala Agricultural University from May 2022 to November 2024. Parental genotypes were evaluated in previous years and suitable genotypes were selected for crossing programme. Twenty four hybrids were synthesized by following Line $× $Tester mating design involving three diverse Cytoplasmic Genic Male Sterile (CGMS) lines and eight testers under rain shelter .The Selected females were pollinated with different pollen sources and seeds were collected from the female plants. Pollination was done in the morning between 8.00 am and 11:30 am by shedding dehisced pollens of the respective testers on the well opened female flowers (CGMS lines). The F1 seeds harvested from corresponding female lines were grown for hybrid evaluation and testing combing ability. The genotypes used in study are depicted in Table 1. The seeds of eleven parental lines, the twenty four F1 s along with standard check ,Sierra were sown in portrays filled with a 3:1:1 mixture of cocopeat, vermiculite, and perlite. The nursery was properly maintained, and thirty-day-old seedlings were transplanted under a rain shelter structure in a Randomized Block Design (RBD) with two replications. Transplanting was done on ridges and furrows with spacing ranging from 45 $×$ 45 cm to 45 $× $60 cm. Twenty four hybrids along with eleven parent and one commercial hybrid check, Sierra were evaluated for various growth and yield parameters. Crop management was done based on the Adhoc recommendation by Kerala Agricultural University (KAU,2016). Observations for various growth and yield traits were recorded from five randomly selected plants, and the mean values were documented. Statistical analysis for the computation of combining ability in the Line × Tester (L × T) mating design, along with analysis of variance, was carried out using the GRAPES Agri1 package in R software (Gopinath et al., 2021)

**Table 1. List of genotypes used in study**

|  |  |  |
| --- | --- | --- |
| **SL no**  | **Genotypes**  | **Sources**  |
|  | **Lines**  |  |
| 1 | AVPP9907 | World Vegetable Centre, Taiwan  |
| 2 | AVPP0516 | World Vegetable Centre, Taiwan  |
| 3 | AVPP0517 | World Vegetable Centre, Taiwan  |
|  | **Tester**  |  |
| 1 | AVPP9703 | World Vegetable Centre, Taiwan  |
| 2 | VI059382 | World Vegetable Centre, Taiwan  |
| 3 | Chivar-1 | IIVR, Varanasi |
| 4 | EC37862 | NBPGR, New Delhi |
| 5 | EC 566920 | NBPGR, New Delhi |
| 6 | LC 217 | Local collection  |
| 7 | Anugraha  | KAU, Vellanikkara  |
| 8 | Ujwala | KAU, Vellanikkara  |

3. results and discussion

ANOVA for combining ability (Table 2) demonstrated, significant mean sum squares for parents, crosses, and parents vs. crosses for most traits, indicating a broad range of variability among the parental lines, hybrids, and their interactions. This variability among parents can be effectively utilized through selection by analyzing heterosis, general combining ability, and specific combining ability. *Per se* performance should not be ignored but given equal importance when assessing economic heterosis, with the ultimate goal of identifying superior hybrids. Mean sum of square due to parents vs hybrids showed significant differences except for primary branch plant-1 ,average fruit weight, and fruit length. Lines and testers were shown variation for all the studied characters. The differences due to line$ × $tester interactions were significant for all the traits supported by earlier findings of Meena, et al., 2018; Lata, 2022).This indicates the presence of wide genetic variability in the studied material, providing an excellent opportunity to identify superior general combiners and to develop promising hybrids.

 *Per se* performance revealed significant differences across various traits among twenty four hybrids (Table 5) and (Table 6). The hybrids AVPP0516$ × $Anugraha, AVPP0517$ × $VI059328, AVPP9907$ ×$ Ujjwala excelled their performance based on superiority of average fruit weight, fruit length, and fruits plant-1 . Growth parameters like plant height was found to be maximum in AVPP0516$ × $Chivar-1(126.10 cm) followed by the hybrid AVPP9907$×$ EC566920 (123.60 cm) which was on par with AVPP0517$ ×$ EC566920 (123 cm). Multiple researchers have also emphasized the excellence of hybrids for various traits utilizing male sterile lines in chilli (Shangargouda , 2013; Siddappa et al., 2017; Meena , 2020b). Primary branches plant-1 found highest in AVPP0516$ × $LC217. Among the crosses, AVPP9907$ × $Ujjwala had the highest number of secondary branches plant-1. Vegetative parameters have a profound impact on overall performance of a plant. Plant spread found maximum in AVPP0517$ × $EC566920. The earliest days of first flowering recorded by AVPP0516 $×$ Chivar-1 (30.70 days). Similar variation for days to first flowering was reported by (Prasath and Ponnuswami, 2008; Bhutia *e*t al*.,* 2015). The same cross was found to be the earliest in fruiting and reaching maturity for harvesting. AVPP0516$ × $AVPP9703 had the maximum average fruit weight (8.67g) and fruit length (12.02 cm). Highest fruits plant-1 exhibited by the cross AVPP0516 $×$ Anugraha (179) followed by AVPP9907 $× $Ujjwala (172.60).The same hybrids exhibited the highest yield plant-1 attaining 822.12 g and 820.80 g, respectively. Previous studies on male sterile lines reported that, MS-6$ ×$ Solan Bharpur identified as supreme in terms of number of fruit and yield plant-1 , while MS-7$ ×$ UHF-CAP-27 had the maximum plant spread ( Rana, 2022). Thirteen CGMS hybrids released by IIHR excelled in yield and yield related taits. Arka Nihira exhibited the highest green fruit yield (1.63 kg plant plant-1), followed by Arka Yashasvi, H-25, H-26 and Arka Tanvi (Khapte et al, 2023).

 Combining ability of the parents (Table 3) revealed that male sterile line AVPP0516 had a positive significant GCA for secondary branch (0.56), plant spread (9.46), average fruit weight (0.36) and fruit length (0.37). Similarly, AVPP0517 was found to be good combiner for plant spread (9.96), days to maturity (0.15) and fruits plant-1 (3.70). Potential of male sterile line as an excellent general combiner is noteworthy in genetic improvement of Chilli. Earlier findings suggested that, male sterile lines CA1450 and DPChMS9-2 proved to be strong general combiners for fruit plant-1 and marketable yield, while Ms-12 also showed robust performance across various growth and yield traits (Payakkabab et al., 2012; Lata et al., 2023). Negative GCA for fruiting and flowering is a desirable trait for marketable yield. AVPP0516 had negative GCA for these traits. Among the tester, VI059382 and Anugraha (166.90) had negative GCA for days to first flowering, fruiting and maturity. The line AVPP0907 proved to be a good combiner for average fruit weight (0.31), fruit length (0.9) and yield plant-1 (27.11). Considering other traits, potential donors for fruits plant-1 was noticed Ujwala (55.28), while the highest yield plant-1 was recorded by Ujwala (222.10) followed by VI059382 (151.83), Anugraha (145.23), and AVPP9703(60.16), respectively.

 Estimates of SCA for certain crosses (Tables 5 and 6) were used to identify the best combiners based on their positive and significant combining ability. Identifying the best parental combiners in breeding helps in selecting suitable cross combinations. The heterotic performance of hybrids can be assessed by evaluating the most effective parental combiners. The estimation of heterosis is based on the SCA of the hybrids, which determines their overall superiority. Current study identifies various combiners associated with different traits. The SCA effects for fruits plant-1 ranged from -26.79.10 to 34.25, with a maximum in hybrids AVPP0516 $×$ Anugraha (34.25), AVPP0517 $×$ VI059382 (31.36) and AVPP9907$ × $Ujjwala (20.80). These crosses are also exhibited desirable SCA for yield plant-1 with maximum in AVPP0516 $×$ Anugraha (76.55), and AVPP0517$ × $VI059382 (172.5) respectively. GMS derived chilli hybrids MS 9-2 $× $HPM-2 was found significantly positive SCA for yield related trait (Lata & Sharma, 2024). Among the hybrids, only AVPP0517$ × $LC 217 exhibited a positive significant SCA for plant height. Maximum significantly positive SCA was recorded in AVPP9907$ ×$ VI05932 for primary branches plant-1. The highest SCA for plant spread recorded in AVPP9907$ × $AVPP9703 (12.94). A notable negative and significant SCA effect for days to first flowering, fruiting, and maturity was observed in the crosses AVPP0516 $×$ AVPP9703, AVPP0516 $×$ Ujwala, and AVPP9907 $×$ EC37862. The highest and significantly positive SCA was observed in AVPP0516$ × $AVPP9703 (1.08) for average fruit weight followed by AVPP9907$ × $EC566920. Earlier studies on male sterile hybrids identified MS 341$ × $PP 402 had high SCA for plant height, SD 463 $×$ PS 403 for plant spread (Sing et al., 2014). Specific combining ability involving male sterile lines were well corroborated by several previous report (Meena et al., 2020b; Rani et al., 2022).

 Perusal of nature of gene action (Table 2 ) showed that additive variance (σ² GCA) was lower than dominant variance (σ² SCA), indicating a predominance of non-additive gene action. As a result, the estimated magnitude of gene action was less than unity, suggesting that heterosis breeding would be an effective strategy for improving all the traits studied. notably the specific crosses such as AVPP0516$ ×$ Anugraha, AVPP0517$ ×$ VI059382 and AVPP9907$ × $Ujjwala demonstrated exceptional *per se* performance, in terms of fruit and yield plant-1 .Hence, these crosses are highly recommended for developing superior heterotic hybrids in chilli. In this study, the *per se* performance of parents emerged as a key criterion for selecting heterotic hybrids, especially for yield and fruit and yield plant-1 .The presence of favorable dominant alleles in hybrids with high SCA is likely responsible for the manifestation of superior heterosis.

**Table 2. Analysis of variance for combining ability in chilli**

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Sources**  | **df** | **PH**  | **PB** | **SB** | **PS**  | **DFF**  | **DFR** | **DM**  | **AFW** | **FL** | **FPP** | **YPP** |
| Replication  | 1 | 21.065 | 0.12 | 6.62 | 14.99 | 13.27 | 18.70 | 14.90 | 0.009 | 0.10 | 5.00 | 883.4535 |
| Genotypes  | 34 | 215.59\*\* | 1.53\*\* | 22.76\* | 522.59\*\* | 22.93\*\* | 20.88\* | 24.42\*\* | 5.92\*\* | 6.69\*\* | 2319.981\*\* | 53909.57\*\* |
| Parents  | 10 | 265.77\*\* | 1.75\*\* | 23.48 \*\* | 531.84\*\* | 36.78\*\* | 36.95\*\* | 37.40\*\* | 12.29\*\* | 7.51\*\* | 539.27\*\* | 219968.70\*\* |
| Parent Vs hybrids | 1 | 565.180\*\* | 0.78 | 234.88 \*\* | 222.20\* | 55.76\*\* | 50.37\*\* | 78.11\*\* | 0.07 | 2.08 | 4062.72\*\* | 183030.33\*\* |
| hybrids | 23 | 178.58\*\* | 1.46\* | 10.64 \*\* | 531.63\*\* | 15.48\*\* | 12.61\*\* | 16.44\*\* | 3.41\*\* | 6.54\*\* | 3018.43\*\* | 62170.71\*\* |
| Lines (female) | 2 | 237.41 | 0.19 | 12.75 | 4529.96\*\* | 28.00 | 20.14 | 19.76 | 5.49\*\* | 21.27 | 437.95 | 19950.1781 |
| Tester(males) | 7 | 322.123\*\* | 1.88 | 20.99\*\* | 57.94 | 25.30 | 22.08 | 32.08 | 8.19\*\* | 11.92 | 8192.02\* | 161978.71\*\* |
| Lines $×$ tester  | 14 | 98.41\*\* | 1.43\*\* |  5.16\*\* | 197.28\*\* | 8.79\*\* | 6.79\*\* | 8.14\*\* | 0.74\*\* | 1.74\*\* | 800.27\*\* | 18298.221\*\* |
| Error | 34 | 25.63 | 0.36 | 0.92 | 42.80 | 1.09 | 1.10 | 1.16 | 0.06 | 0.14 | 47.710 | 851.96 |

*Df- Degrees of freedom, PH-Plant height, PB-Primary branches plant-1 , SB – Secondary branches plant-1 ,PS-plant spread, DFF-Days to first flowering ,DFR-Days to fruiting, AFW-Average fruit weight, DM-Days to maturity, FL-Fruit length , FPP-Fruits plant-1 , YPP-Yield plant-1*

\* Significant at 5 % level \*\* Significant at 1 % level

**Table 3 Genetic components of variances in chilli**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Source of variation**  | **PH**  | **PB** | **SB** | **PS**  | **DFF**  | **DFR** | **DM**  | **AFW** | **FL** | **FPP** | **YPP** |
| σ² GCA  | 5.53 | 0.003 | 0.37 | 23.09 | 0.46 | 0.40 | 0.57 | 0.18 | 0.33 | 153.20 | 3030.232 |
| σ² SCA | 36.38 | 0.56 | 2.1 | 77.23 | 3.85 | 2.84 | 3.48 | 0.34 | 0.80 | 376.28 | 8723.126 |
| Additive variance/dominance variance  | 0.15 | 0.00 | 0.17 | 0.29 | 0.11 | 0.14 | 0.16 | 0.52 | 0.41 | 0.40 | 0.34 |

*PH-Plant height, PB-Primary branches plant-1 , SB – Secondary branches plant-1 ,PS-plant spread, DFF-Days to first flowering ,DFR-Daya to fruiting, AFW-Average fruit weight, DM-Days to maturity, FL-Fruit length , FPP-Fruits plant-1 , YPP-Yield plant-1*

**Table 4. Estimates of GCA effects of parents for growth and yield characters in chilli**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Parents**  | **PH** | **PB** | **SB** | **PS** | **DM**  | **DFF** | **DFR** | **AFW** | **FL** | **FPP** | **YPP** |
| **Line**  |  |  |  |  |  |  |  |  |  |  |  |
| AVPP0516 | -0.77 | 0.12 | 0.56\* | 9.46\*\* | -1.81\*\* | -1.27\*\* | -1.12\*\* | 0.36\*\* | 0.37\*\* | 2.28 | 12.813 |
| AVPP0517 | -3.40\*\* | -0.09 | -1.02\*\* | 9.96\*\* | 0.15 | -0.192 | -0.01 | -0.67\*\* | -1.29\*\* | 3.70\* | -39.929\*\* |
| AVPP09907 | 4.17\*\* | -0.02 | 0.46 | -19.42\*\* | 1.02\*\* | 1.40\*\* | 1.13\*\* | 0.31\*\* | 0.9\*\* | -5.98\*\* | 27.116\*\* |
| **Tester** |  |  |  |  |  |  |  |  |  |  |  |
| AVPP9703 | -4.12 | 0.13 | -2.77\*\* | 4.65 | 1.74\*\* | 1.59\*\* | 1.46\*\* | 2.65\*\* | 2.45\*\* | -22.93\*\* | 60.16\*\* |
| VI059328 | -10.17\*\* | -0.36 | -1.46\*\* | -3.36 | -4.20\*\* | -3.59\*\* | -3.51\*\* | -0.9\*\* | -1.72\*\* | 33.58\*\* | 151.83\*\* |
| Chivar-1 | 6.29\*\* | 0.86\*\* | -0.21 | -1.31 | -0.72\* | 0.22 | 0.100 | -0.83\*\* | -1.31\*\* | -37.53\*\* | -202.12\*\* |
| EC566920 | 9.67\*\* | -0.76\*\* | -0.14 | 1.86 | 3.07\*\* | 2.69\*\* | 2.46\*\* | -0.05 | -0.85 | -34.48\*\* | -174.64\*\* |
| EC37862 | 7.39\*\* | -0.23 | -1.04 | 2.15 | 0.31 | 0.45 | 0.16 | 0.16 | -0.33\* | -18.48\*\* | -100.68\*\* |
| LC 217 | 0.47 | -0.33 | 0.88 | -3.51 | -0.02 | -0.44 | -0.30 | 0.20\* | 1.51\*\* | -16.06\*\* | -101.88\*\* |
| Anugraha  | -8.05\*\* | -0.06 | 1.55\*\* | 2.25 | -1.90\*\* | -2.19\*\* | -1.76\*\* | -0.40\*\* | 0.003 | 40.61\*\* | 145.23\*\* |
| Ujwala  | -1.50 | 0.72\*\* | 3.24\*\* | -2.17 | 1.72\*\* | 1.25\*\* | 1.38\*\* | -0.83\*\* | 0.26 | 55.28\*\* | 222.10\*\* |

*PH-Plant height, PB-Primary branches plant-1 , SB – Secondary branches plant-1 ,PS-plant spread, DFF-Days to first flowering ,DFR-Days to fruiting, AFW-Average fruit weight, DM-Days to maturity, FL-Fruit length , FPP-Fruits plant-1 , YPP-Yield plant-1*

\* Significant at 5 % level \*\* Significant at 1 % level

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Hybrids**  | **MEAN**  | **PH**  | **MEAN**  | **PS**  | **MEAN**  | **PB** | **MEAN**  | **SB**  | **MEAN**  | **DFF**  | **MEAN**  | **DFR**  |
| AVPP0516$×$AVPP9703 | 99.25 | -7.77\* | 81.80 | 1.40 | 4.3 | -0.42 | 11.95 | -1.11 | 32.05 | -2.86\*\* | 36.00 | -2.25\*\* |
| AVPP0516$×$ VI059328 | 105.40 | 4.42 | 74.55 | 2.17 | 3.10 | -1.12\*\* | 13.38 | -0.58 | 30.70 | 0.96 | 33.60 | 0.32 |
| AVPP0516$×$Chivar-1 | 126.10 | 8.65\* | 66.05 | -8.37 | 6.00 | 0.54 | 16.15 | 0.51 | 34.30 | 0.75 | 37.65 | 0.76 |
| AVPP0516$×$EC566920 | 108.20 | -2.62 | 83.20 | 5.59 | 3.40 | -0.42 | 17.00 | 1.30 | 35.40 | -0.61 | 38.55 | -0.70 |
| AVPP0516$×$ EC37862 | 119.50 | 4.54 | 79.20 | 1.30 | 4.70 | 0.34 | 17.60 | 2.80\*\* | 36.50 | 2.71\*\* | 39.40 | 2.44\*\* |
| AVPP0516$×$LC 217 | 99.15 | -12.47\*\* | 68.00 | -4.22 | 5.80 | 1.54\*\* | 14.65 | -2.08\*\* | 33.40 | 0.51 | 36.55 | 0.06 |
| AVPP0516$×$Anugraha  | 105.80 | 2.70 | 77.05 | -0.94 | 4.90 | 0.07 | 16.60 | -0.79 | 32.65 | 1.51\* | 36.45 | 1.42 |
| AVPP0516$×$Ujjwala  | 112.30 | 2.65 | 76.10 | 3.07 | 4.80 | -0.54 | 19.00 | -0.04 | 31.60 | -2.98\*\* | 36.10 | -2.07\*\* |
| AVPP0517$×$AVPP9703 | 108.00 | 3.60 | 66.55 | -14.35\*\* | 5.60 | 1.09\*\* | 12.40 | 0.92 | 35.05 | -0.89 | 38.00 | -1.34 |
| AVPP0517$×$ VI059328 | 92.55 | -5.79 | 59.65 | -13.23\*\* | 4.00 | -0.00 | 12.05 | -0.73 | 31.05 | 0.29 | 34.95 | 0.58 |
| AVPP0517$×$Chivar-1 | 109.20 | -5.60 | 76.85 | 1.91 | 5.00 | -0.23 | 14.05 | 0.01 | 34.60 | 0.02 | 37.95 | -0.03 |
| AVPP0517$×$EC566920 | 123.00 | 4.80 | 84.10 | 5.98\* | 3.80 | 0.19 | 15.20 | 1.09 | 37.90 | 0.85 | 41.30 | 0.95 |
| AVPP0517$×$EC37862 | 115.30 | -0.60 | 89.10 | 10.70\* | 3.70 | -0.73 | 12.00 | -1.20 | 34.30 | -0.50 | 37.80 | -0.24 |
| AVPP0517$×$LC 217 | 121.000 | 12.00\*\* | 74.10 | 1.36 | 3.55 | -0.73 | 15.85 | 0.71 | 32.80 | -1.10 | 36.85 | -0.73 |
| AVPP0517$×$Anugraha  | 97.10 | -3.35 | 84.10 | 6.20 | 3.90 | -0.40 | 15.05 | -0.75 | 32.40 | 0.24 | 36.40 | 0.28 |
| AVPP0517$×$Ujjwala  | 101.95 | -5.05 | 74.95 | 1.41 | 5.95 | 0.82\* | 17.40 | -0.05 | 36.70 | 1.09 | 39.80 | 0.53 |
| AVPP9907$×$AVPP9703 | 116.15 | 4.17 | 64.45 | 12.94\*\* | 4.10 | -0.67 | 13.15 | 0.18 | 41.30 | 3.75\*\* | 44.10 | 3.60\*\* |
| AVPP9907$×$VI059328 | 107.30 | 1.37 | 54.55 | 11.06\* | 5.20 | 1.12\*\* | 15.60 | 1.31 | 31.10 | -1.25 | 34.60 | -0.91 |
| AVPP9907$×$Chivar-1 | 119.35 | -3.04 | 52.00 | 6.46 | 5.00 | -0.30 | 15.00 | -0.53 | 35.40 | -0.77 | 38.40 | -0.73 |
| AVPP9907$×$EC566920 | 123.60 | -2.17 | 37.17 | -11.57\* | 3.90 | 0.22 | 13.20 | -2.39\*\* | 38.40 | -0.24  | 41.25 | -0.24 |
| AVPP9907$×$EC37862 | 119.65 | -3.84 | 37.00 | -12.00\* | 4.60 | 0.39 | 13.10 | -1.59\* | 34.20 | -2.20\*\* | 37.00 | -2.19\*\* |
| AVPP9907$×$LC 217 | 117.05 | 0.47 | 46.20 | 2.86 | 3.30 | -0.80\* | 18.00 | 1.36\* | 36.10 | 0.59 | 39.40 | 0.66 |
| AVPP9907$×$Anugraha  | 108.70 | 0.65 | 43.85 | -5.25 | 4.70 | 0.32 | 18.85 | 1.55\* | 32.00 | -1.75\* | 35.55 | -1.71\* |
| CD(0.05) | 11.06 |  | 14.32 |  | 1.02 |  | 1.82 |  | 2.05 |  | 2.07 |  |
| CV(%) | 5.04 |  | 10.45 |  | 11.01 |  | 5.79 |  | 2.85 |  | 2.64 |  |

**Table 5. Estimates of SCA effects and *per se* performance of chilli hybrids for growth and yield characters**

*Secondary branches plant-1 ,PS-Plant spread, DFF-Days to first flowering ,DFR-Days to fruiting, AFW-Average fruit weight, DM-Days to maturity, FL-Fruit length , FPP-Fruits plant-1 , YPP-Yield plant-1*

\* Significant at 5 % level \*\* Significant at 1 % level

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Hybrids**  | **MEAN**  | **DM** | **MEAN**  | **AFW** | **MEAN**  | **FL** | **MEAN**  | **FPP** | **MEAN**  | **YPP** |
| AVPP0516$×$AVPP9703 | 54.55 | -2.31\*\* | 8.67 | 1.08\*\* | 12.020 | 0.91\*\* | 75.20 | -6.65 | 539.050 | -21.440 |
| AVPP0516$×$ VI059328 | 51.02 | 0.53 | 3.72 | -0.30 | 5.610 | -1.32\*\* | 133.80 | -4.56 | 572.58 | -79.581\*\* |
| AVPP0516$×$Chivar-1 | 54.25 | 0.24 | 3.55 | -0.55\*\* | 8.280 | 0.94\*\* | 68.10 | 0.85 | 220.82 | -77.371\*\* |
| AVPP0516$×$EC566920 | 57.00 | -0.80 | 4.05 | -0.83\*\* | 8.390 | 0.58\* | 83.55 | 13.25\*\* | 303.31 | -22.360  |
| AVPP0516$×$ EC37862 | 57.15 | 2.11\*\* | 5.46 | 0.36\* | 7.650 | -0.67\* | 88.30 | 2.00 | 432.67 | 33.037  |
| AVPP0516$×$LC 217 | 54.50 | -0.20 | 5.42 | 0.28 | 9.200 | -0.96\*\* | 68.60 | -20.11\*\* | 407.03 | 8.595 |
| AVPP0516$×$Anugraha  | 54.55 | 1.73\* | 4.69 | 0.16 | 8.990 | 0.33 | 179.65 | 34.25\*\* | 822.120 | 176.55\*\* |
| AVPP0516$×$Ujjwala  | 55.15 | -1.30 | 3.90 | -0.19 | 9.100 | 0.18 | 141.05 | -19.01\*\* | 704.985 | 17.44 |
| AVPP0517$×$AVPP9703 | 56.75 | -1.05 | 6.09 | -0.46\* | 8.590 | -0.84\*\* | 93.40 | 10.13\* | 567.53 | 59.78\*\* |
| AVPP0517$×$ VI059328 | 50.90 | -0.95 | 3.52 | 0.52\*\* | 6.740 | 1.47\*\* | 171.15 | 31.36\*\* | 771.99 | 172.57\*\* |
| AVPP0517$×$Chivar-1 | 55.15 | -0.19 | 3.47 | 0.40\* | 5.680 | 0.01 | 66.40 | -2.26 | 244.525 | -2.429  |
| AVPP0517$×$EC566920 | 59.45 | 0.31 | 3.76 | -0.08 | 5.390 | -0.74\* | 61.60 | -10.11\* | 273.03 | 0.102 |
| AVPP0517$×$EC37862 | 57.00 | 0.62 | 4.10 | 0.03 | 7.560 | 0.90\*\* | 81.85 | -5.86 | 337.140 | -9.751 |
| AVPP0517$×$LC 217 | 55.55 | -0.49 | 4.17 | 0.07 | 8.980 | 0.48 | 93.00 | 2.86 | 301.820 | -43.87\*\* |
| AVPP0517$×$Anugraha  | 56.05 | 1.89\* | 2.95 | -0.53\*\* | 6.370 | -0.61\* | 122.50 | -24.31\*\* | 483.050 | -109.76\*\* |
| AVPP0517$×$Ujjwala  | 57.65 | -0.14 | 3.10 | 0.04 | 6.580 | -0.66\* | 159.70 | -1.78 | 603.050 | -66.63\*\* |
| AVPP9907$×$AVPP9703 | 62.05 | 3.37\*\* | 6.93 | -0.61\*\* | 11.590 | -0.06 | 70.10 | -3.48 | 536.450 | -38.343\*\* |
| AVPP9907$×$VI059328 | 53.15 | 0.42 | 3.76 | -0.21 | 7.320 | -0.15 | 103.30 | -26.79\*\* | 573.475 | -92.98\*\* |
| AVPP9907$×$Chivar-1 | 56.15 | -0.05 | 4.20 | 0.15 | 6.930 | -0.95\*\* | 60.40 | 1.41 | 392.300 | 79.80 \*\* |
| AVPP9907$×$EC566920 | 60.50 | 0.49 | 5.75 | 0.91\*\* | 8.500 | 0.15 | 58.90 | -3.13 | 362.235 | 22.25 |
| AVPP9907$×$EC37862 | 54.50 | -2.74\*\* | 4.65 | -0.40\* | 8.630 | -0.23 | 81.90 | 3.86 | 390.650 | -23.28 |
| AVPP9907$×$LC 217 | 57.60 | 0.69 | 4.73 | -0.35\* | 11.195 | 0.48 | 97.70 | 17.25\*\* | 448.015 | 35.27 |
| AVPP9907$×$Anugraha  | 51.40 | -3.62\*\* | 4.85 | 0.37\* | 9.490 | 0.28 | 127.20 | -9.93\* | 593.075 | -66.78 \*\* |
| AVPP9907$×$Ujjwala  | 60.10 | 1.44 | 4.20 | 0.15 | 9.940 | 0.48 | 172.60 | 20.80 | 820.80 | 84.07\*\* |
| CV(%) | 4.25 |  | 0.55 |  | 0.81 |  | 15.57 |  | 100.11 |  |
| CD(0.05) | 3.67 |  | 5.86 |  | 4.85 |  | 7.34 |  | 9.92 |  |

**Contd .Table 6. Estimates of SCA effects and *per se* performance of chilli hybrids for growth and yield characters**

*PH-Plant height, PB-Primary branches plant-1 SB – Secondary branches plant-1 ,PS-Plant spread, DFF-Days to first flowering ,DFR-Days to fruiting, AFW-Average fruit weight, DM-Days to maturity, FL-Fruit length , FPP-Fruits plant-1 , YPP-Yield plant-1*

\* Significant at 5 % level \*\* Significant at 1 % level

4.Conclusion

The integration of male sterility could significantly reduce the labor intensive emasculation process, thereby reducing hybrid seed production cost. The present study identifies three superior crosses (AVPP0516 $× $Anugraha (176.55) and AVPP0517 $×$ VI059382 (172.57, AVPP9907 $× $ Ujjwala with higher SCA for yield contributing traits, highlighting their potential for maximising heterotic performance. furthermore, the study generates different donor parents with strong GCA for specific traits, making them valuable candidates for future chilli breeding. Breeders can utilise male sterile lines as parents by considering combining ability, gene interaction and other various gene linkage studies, that would allow favorable allelic interaction in specific traits which shall pave in the development of heterotic hybrids.

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Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**REFERENCES**

1. Herath, H. N., Rafii, M.Y., Ismail, S.I., JJ, N. & Ramlee, S. I. (2021). Improvement of important economic traits in chilli through heterosis breeding: a review. The Journal of Horticultural Science and Biotechnology, *96*(1), 14-23. <https://doi.org/10.1080/14620316.2020.1780162>.
2. Thakur, H., Jindal, S. K., Sharma, A., & Dhaliwal, M. S. (2019). A monogenic dominant resistance for leaf curl virus disease in chilli pepper (*Capsicum annuum* L.). Crop Protection, 116, 115-120. <https://doi.org/10.1016/j.cropro.2018.10.007>.
3. Indiastat. Area, production and productivity of chilli in India. Accessed November 2024. Available:https://www.indiastat.com/table/agriculture/area-production-productivity chilli -India.
4. FAOSTAT. 2022. Statistics Division, Food and Agriculture Organization of the UN. Food and Agriculture Organization of the UN. <https://www.fao.org/faostat/en/#data>.
5. Dhaliwal, M.S. & Jindal, S.K. ( 2014). Induction and exploitation of nuclear and cytoplasmic male sterility in pepper (*Capsicum* spp.): a review. The Journal of Horticultural Science and Biotechnology, *89*(5), 471-479. <https://doi.org/10.1080/14620316.2014.11513108>.
6. Lata, H., Sharma, A., Thakur, H., Thakur, A., Rana, R. S., & Kaur, M.( 2023). Heterosis and combining ability vis‐à‐vis association for green fruit yield and component traits involving male sterile lines in chilli (*Capsicum annuum*) under wet temperate zone of North Western Himalayas. Plant Breeding, 142 (4), 547-562

.

1. Kadambavanasundaram M. (1980 ). Heterotic system in cultivated species of Gossypium. An appraisal (Abst). Genetic and crop improvement of heterotic systems. Precongress scientific meeting of XV International Congress of Genetics, TNAU, Coimbatore, pp. 20.
2. Chadha, S., Kumar, J.,& Vidyasagar. (2001). Combining ability over environments in tomato. Indian Journal of Agricultural Research, 5 (3), 171-175.
3. Dudley, J. W. & Moll, R. H. (1969). Interpretation and use of estimates of heritability and genetic variances in plant breeding. Crop Science, (9), 257-263. <https://doi.org/10.2135/cropsci1969.0011183X000900030001x>.
4. Manjunath, K.V., Das, S., Mallick, R.G., Hazra, P., Chattopadhyay, A. & Maji, A. (2025). Combining ability and gene action for fruit yield components, quality, shelf life and reaction to tomato leaf curl virus disease. Heliyon, 2e42040. <https://doi.org/10.1016/j.>
5. Prasad, I., Kumar, R., Tiwari, I., Tiwari, C.P., Chaturvedi, V. D., & Singh, P. ( 2025). Hybrid Seed Production of Chilli (*Capsicum annuum* L.) for Sustaining Yield and Profitability. In Hybrid Seed Production for Boosting Crop Yields*:* Applications, Challenges and Opportunities, 409-429). Singapore: Springer Nature Singapore. <https://doi.org/10.1007/978-981-96-0506-4_15>.
6. Kempthone, O. (1957). An introduction to genetic statistics. John Wiley and sons, Inc.New York,545p
7. KAU (Kerala Agricultural University) (2016) .Package of Practices Recommendations: Crops (15 th Ed.). Kerala Agricultural University, Thrissur.; 393.
8. Gopinath P. P., Parsad, R., Joseph, B., & Adarsh, V. S. (2021). Grapes Agri1: Collection of shiny apps for data analysis in agriculture. Journal Open Source Software , 6 (63), 3437. https://doi.org/10.21105/joss.034 37.
9. Meena, O. P., Dhaliwal, M. S., & Jindal, S. K. (2018). Development of cytoplasmic male sterile lines in chilli (*Capsicum annuum* L.) and their evaluation across multiple environments. Breeding Science, 2068, 404-412. <https://doi.org/10.1270/jsbbs.17150>.
10. Lata, H. (2022). Heterosis and combining ability studies in male sterility based F1 hybrids of chilli (*Capsicum annuum* L.) Ph. D thesis, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur.
11. Shankargouda, S.(2013). Exploitation of male sterility in development of f1 hybrids in chilli,M. Sc. (Hort.) Thesis, University of Agricultural Sciences., Dharwad India.
12. Siddappa, S., Ravindra, M., & Shashikanth, E . (2019). Combining ability analysis in Chilli (Capsicum annum L.). Agricultural Science Digest-A Research Journal , 39(3), 220-223.
13. Meena, O.P., Dhaliwal, M. S., & Jindal, S. K. (2020a). Heterosis breeding in chilli pepper by using cytoplasmic male sterile lines for high-yield production with special reference to seed and bioactive compound content under temperature stress regimes. Scientia Horticulturae. , 262 , 109036. <https://doi.org/10.1016/j.scienta.2019.109036>.
14. Prasath, D., & Ponnuswami, V. (2008). Heterosis and combining ability for morphological, yield and quality characters in paprika type chilli hybrids. Indian Journal of Horticulture , 65(4), 441-445.
15. Bhutia, N. D., T. Seth, V. D., Shende, S., Dutta, & Chattopadhyay, A. (2015). Estimation of heterosis, dominance effect and genetic control of fresh fruit yield, quality and leaf curl disease severity traits of chili pepper (*Capsicum annuum. L*.) Scientia Horticulturae, 182, 47–55. <https://doi.org/10.1016/j.>
16. Rana, s.( 2022). Line $×$Tester analysis in bell pepper *(Capsicum annuum l*.) using male sterile lines. Ph. D thesis, Dr. Yashwant Singh Parmar University of Horticulture and Forestry.
17. Khapte, P. S., Ponnam, N., Boraiah, K. M., Wakchaure, G. C., & Gurumurthy, S.(2023) . Genetic variations and character association among CGMS based chilli F1 hybrids for morphometric, fruit quality, and yield traits in shallow basaltic soils of India. Indian Journal of Horticulture. 2, 80 (4), 353-359. https://doi.org/10.25081/jpc.2020 .v48.i3.6628.
18. Payakhapaab, S., Boonyakiat, D., & Nikompun, M. E 2012. Evaluation of combining ability of yield components in Chillies. Indian Journal of Horticulture ,4 (11), 154-161.
19. Lata, H, & Sharma, A. (2024). Exploitation of heterosis in chilli using genetic male sterile lines for red fruit yield with special reference to high rainfall conditions. Scientific Reports. , 14 (1) , 23061.https://doi.org/10.1038/s41598-024-73728-7.
20. Singh, P., Cheema, D. S., Dhaliwal, M. S., & Garg, N.(2014). Heterosis and combining ability for earliness, plant growth, yield and fruit attributes in hot pepper (*Capsicum annuum* L.) involving genetic and cytoplasmic-genetic male sterile lines. Scientia Horticulturae, 168, 175-188. <https://doi.org/10.1016/j.031scienta.2013.12.>
21. Shankargoud, S., Ravindra, M.,& Evoor, S.(2017). Heterosis for growth, earliness and yield in CGMS based hybrids chilli (*Capsicum annum* L.). Buletin of Environment . Pharmacology and Life Science, 6 , 34–38.
22. Meena, O. P., Dhaliwal, M.S., Jindal, S.K., & Rani M. (2020b). Cytoplasmic male sterile lines with desirable combining ability enhance the concentration of biochemical attributes and total yield in Capsicum annuum under temperature stress conditions. Industrial Crops & Products, 145, 1-17. Available: <https://doi.org/10.1016/j.>
23. Rani, M., Jindal, S. K., & Meena, O. P.(2022) . Exploitation of heterosis among phenotypically diverse capsicum parents for important fruit traits. *Brazilian Archives of Biology and Technology*, *64*, p.e21200597. <https://doi.org/10.1590/1678-4324-2021200597>.