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Ankush Chaudhary

Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Happy Dev Sharma

Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Amit Vikram

Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Meenu Gupta

Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Vipin Sharma

Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Anuj Sohi

anujssohi@gmail.com

Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Prakash Singathiya

Indian Institute of Horticultural Research

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Evaluation of open-pollinated chilli lines for heterosis and combining ability under diverse Himalayan environments

Ankush Chaudhary¹, Happy Dev Sharma^{1*}, Amit Vikram¹, Meenu Gupta², Vipin Sharma³, Anuj Sohi^{1,4*} and Prakash Singathiya⁵

¹Department of Vegetable Science, Dr Yashwant Singh Parmar University of Horticulture and Forestry Nauni, Solan, Himachal Pradesh 173 230, India

²Department of Plant Pathology, Dr Yashwant Singh Parmar University of Horticulture and Forestry Nauni, Solan, Himachal Pradesh 173 230, India

³Department of Environmental Science, Dr Yashwant Singh Parmar University of Horticulture and Forestry Nauni, Solan, Himachal Pradesh 173 230, India

⁴Faculty of Agriculture, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala, Haryana 133 207, India

⁵Division of Vegetable Science, Indian Institute of Horticultural Research, Bengaluru, Karnataka 560 089, India

*Corresponding author's email: anujsssohi@gmail.com; ankushchaudhary2613@gmail.com

ABSTRACT

Superior quality chilli for red ripe yield, processing, and pharmaceutical use is a major breeding objective in chilli. An experiment was conducted at three locations under diverse Himalayan agro-climatic zones. Twenty-one F₁ hybrids were developed by crossing seven diverse genotypes using a half diallel mating design to evaluate heterosis, per se performance and combining ability in a Randomized Complete Block design with three replications during summer 2021 and 2022. The open-pollinated varieties Him Palam Mirch 2, Punjab Guchhedar, Pusa Jwala and Pusa Sadabahar showed significant general combining ability to profitable dry/red fruit yield and most contributing traits. For red ripe fruit yield on per se performance ten F₁ hybrids has been identified as superior for significant heterosis and specific combining ability effects, including Him Palam Mirch 2 × Punjab Guchhedar, Pusa Sadabahar × DKC-8, Him Palam Mirch 2 × Him Palam Mirch 1, Pusa Jwala × Punjab Guchhedar, Him Palam Mirch 2 × Pusa Jwala, Him Palam Mirch 2 × DKC-8, Pusa Jwala × DKC-8, Surajmukhi × Pusa Sadabahar, Him Palam Mirch 2 × Pusa Sadabahar and Him Palam Mirch 1 × DKC-8 across locations. A significant positive correlation of specific combining ability with economic heterosis and F₁ performance was observed for most traits. Beyond conventional heterosis analysis, this study integrates multi-location evaluation to identify hybrids with stable adaptability and resilience traits. The dual utility of these hybrids for spice processing and pharmaceutical applications, along with their climate-resilient potential, provides new directions for chilli improvement programmes.

Keywords: *Heterosis, Combining ability, Correlation Coefficient, Half diallel, Open pollinated*

INTRODUCTION

Chilli (*Capsicum annum L.*) is the world's most commercially important spice and vegetable crops and for fresh consumption, dried spice production, processing, export and medicinal use (Dijan et al. 2006, Hazra et al. 2011, Bosland and Votava 2000). The crop is predominantly important in tropical and subtropical agriculture as it provides both monetary revenue to farmers and raw materials for the food, pharmaceutical, and nutraceutical sectors (Biswas et al. 2011, Tepic et al. 2008). Southern Mexico is known as the main origin of

Capsicum, with India as the secondary centre of diversification (Thakur et al. 2019). Capsicum genus has generally 31 recognized species, from which 5 species which are domesticated viz. *C. baccatum*, *C. frutescens*, *C. annum*, *C. pubescens* and *C. chinense* (Pickersgill 1991, Moscone et al. 2007). Cytogenetic and evolutionary analyses have discovered that these species have evolved into discrete groups with varying karyotype traits, genome sizes, and geographic divisions (Moscone et al. 2007, Qin et al. 2014). Capsicum diversity in chilli makes it more valuable crop to investigate its domestication, evolution and inheritance pattern of horticultural traits (Walash and Hoot 2001, Moscone et al. 2007).

From global perspective, chilli covered more than 3.8 million hectares area and production about 50.3 million tonnes. China was affirmed to be the largest producer of green chilli, accounting for 39%, while India ranked second if area and production are considered and accounting for 12% of the global share (FOSTAT 2024). In India, chilli is mainly prioritized for both local use and spice trade (Anonymous 2011, Herath et al. 2017). For current scenario, the crop occupies 423,700 hectares area, with yields of 4,588,700 MT and productivity of 10.8 MT/ha. Andhra Pradesh tops India in terms of land area, production, and productivity (Indiastat 2024). However, yield and productivity are often limited by biotic and abiotic stresses and temperature is a primary factor among all, and the use of local and low-yielding or hereditarily unstable materials.

Chilli fruits comprise healthy amount of nutrients, antioxidants, vitamin C, beta-carotene, and other advantageous chemicals (Bhutia et al. 2015, Herath et al. 2020). These nutritional descriptions improve the crop's market value as well as make it valued not only as a spice but also as a useful food ingredient (Olimpia et al. 2017, Mendes et al. 2019). Researchers discovered that fruit production, weight, length and number, vitamin C, capsaicin and oleoresin content are all vital economic characteristics to advance in chilli (Bhutia et al. 2015, Arimboor et al. 2015, Jindal et al. 2015). Capsaicin is the primary most vital quality attribute in chilli having direct effect on pungency, which further influence the choice and processing significance (Nagaraja et al. 2016, Mendes et al. 2019). Capsaicinoids, predominantly di-hydrocapsaicin and capsaicin, contributes in 90% of the hot taste in fruit of chilli (Topuz et al. 2007, Nagaraja et al. 2016, Lyu et al. 2019). Moreover, capsaicin has therapeutic importance in terms of pain relief, weight reduction potential, and cancer inhibition, also capsaicinoids in chilli are valued for food and pharmaceutical businesses (Naresh et al. 2016, Takashi et al. 2001, Srinivasan 2016). Despite these conventional uses, there is limited advancement in integrating nutritional and pharmaceutical traits with breeding strategies, creating scope for novel approaches that include both yield improvement with value-added applications.

Temperature as being an imperative environmental element influence chilli development, flowering and fruit set, and in result the final production, and these effects are significantly optimized when genotypes are assessed across multi locations (Sanati et al. 2018, Medina-Lara et al. 2008). Fruit arrangement differs with environmental circumstances, cultivated variety, and crop management, consequently the same genotype may perform differently if exposed under different thermal regimes (Sanati et al. 2018, Monforte-González et al. 2010, Medina-Lara et al. 2008). As a result, multi-location testing becomes critical for breeders with goal to discover stability and adaptability for both parents and hybrids (Herath et al. 2017, Indiastat 2024, Bhutia et al. 2015). This highlights the prominence of multi-location trials, which not only identifies stable and broadly adaptable lines but also provides resilience under diverse agro-climatic conditions—an advancement beyond conventional breeding and single-location studies.

Cytogenetic findings specify that domesticated peppers advanced along frequent distinct evolutionary lineages (Moscone et al. 2007) which makes chilli an important reservoir of genetic diversity for fruit size, shape, colour, pungency and adaptation, which can be utilized by breeders to produce hybrids and improved traits (Pickersgill 1991, Walash and Hoot 2001). Chilli is also an ideal crop for hybrid development because heterosis is commonly expressed in chilli for yield and quality attributes (Vera-Guzmán et al. 2011). Peppers shows substantial heterotic effects for fruit size, weight, number and yield per plant, vitamin C, and capsaicin content (Bhutia et al. 2015, Singh et al. 2014, Rohini and Lakshmaman 2016). This proves hybridization as an efficient technique for enhancing chilli productivity and fruit quality characters (Rohini and Lakshmaman 2016, Ramesh et al. 2013).

Parent selection in any breeding program is very crucial since combining ability suggest that how effectively a parent plant passes advantageous genes to its progenies (Griging 1956, Sharma et al. 2013). Additive gene action is attributed to (GCA) general combining ability and non-additive effects such as dominance and epistasis is attributed to specific combining ability (SCA) (Baker 1978, Patil and Sawant 2018). While earlier studies have focused on heterosis and combining ability in isolation, the present work advances knowledge by linking these genetic effects with multi-location adaptability and dual-purpose utility (spice and pharmaceutical), thereby offering breeders predictive frameworks for parent selection and hybrid deployment. Different studies on chilli suggested that non-additive gene action controls various yield and quality related parameters and in result makes heterosis breeding more effective rather than simple selection for those attributes (Thilak et al. 2019, Bhutia et al. 2015). Inbred varieties and open pollinated cultivars carry large genetic foundation therefor play a significant role in chilli improvement and can be exploited as parents to develop F₁ hybrids (Herath et al. 2017, Shuro 2017). Overall, the study focuses on improving chilli for high economic, nutritional and medicinal value, and the desired improvement is dependent on the combined use of combining ability analysis, heterosis breeding and selection of genetically diverse parents. Because yield and capsaicin content are often controlled by both additive and non-additive gene effects, breeding programs must carefully assess parents and hybrids before indorsing them for economic use. By integrating heterosis breeding, combining ability analysis, and multi-environment evaluation, this research moves beyond conventional plant breeding to provide novel insights into climate-resilient and value-added chilli improvement programmes.

MATERIALS AND METHODS

Experimental locations

The study is focused on two experiments, first is conducted during march to March, 2021 and second from march to September 2022 at three distinct agroclimatic regions viz., E1: Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, HP (30°51'54"N, 77°10'08'E and 1300 m altitude), E2: Regional Horticulture Research and Training Station, Dhaula Kuan, HP (30°30'20"N, 77°20'30'E and 468 m altitude) and E3: Regional Horticulture Research & Training Station, Dhaula Kuan, HP (32.8°N, 74.7°E and 1090 m altitude) as represented in Fig. 1. According to Indian Meteorological Department (IMD) Shimla and Brief Facts about Himachal Pradesh, Economics and Statistics Department, HP Government, the regions have distinct climates (Hot and dry, cool and humid) and altitudes (Anonymous 2023). The graphical representation of the environmental conditions is presented in Fig. 1.

Development of hybrids and mating design

During 2021, Seven chilli open pollinated lines were used as parents and twenty-one hybrids were synthesized using these OP varieties. The selection of the lines was based on their earliness, plant canopy, production and fruit characteristics, such as fruit weight, TSS and capsaicin content. The lines have different fruit bearing positions (Upright and pendant), developed by different agricultural institutes. The details of all the parental material used in the study is presented in Table 1. The lines were crossed in a half-diallel mating design without reciprocals, resulting in twenty-one hybrid combinations. Pollination was performed between 8:30 and 11:30 am. Hermaphrodite male and flowers were manually pollinated for crossing between the lines. Before anthesis, the hermaphrodite flowers were selected, separated and emasculated. The pollens from male flowers which were removed during the pollination process, were used to fertilize the stigma of female flowers. Red ripe fruits from healthy were extracted for further evaluation.

Genotype evaluation and crop management

During 2022, the seeds of 7 parents including check variety DKC-8 and 21 hybrids were treated with fungicide (Carbendazim) @3g/kg seeds were planted in nursery beds of 3m x 1m x 15 cm size, consecutively at all the three locations, on 21st February, 24th February and 26th February, 2022, respectively with 5 cm row spacing and 2 cm depth. The seedlings of about two months were transplanted. The experiment followed a Randomized Complete Block Design (RCBD) with three replications. Twelve plants with a 90 x 60 cm gap between each plant made up each plot. DKC-8 cultivar is used as control since it is most widely produced in the area. Fertilizers viz. Farm yard manure @ 20 t/ha⁻¹, N, P₂O₅ and K₂O 75:60 and 60 kg respectively, were applied according to recommended dose per acre. During field preparation, the full amount of phosphorus and potassium along with half the nitrogen dose were incorporated into the soil. The remaining dose of N were top dressed in two split applications between one month gap. Twenty-eight treatments in all, including 21 hybrids and seven parental lines, including the check cultivar DKC-8, were assessed for fruit weight, red ripe fruit yield per plant, plant height, fruit numbers, pedicel length, the number of seeds per fruit and capsaicin content for all the three different locations mentioned in Table 1.

Trait Evaluation Methodology

The methodology adopted for trait evaluation is summarized in Table 2, which provides a detailed account of the characteristics studied and their respective methods of assessment. The measurement of plant height extended from ground level to terminal point of primary stem, while fruit weight and fruit number were measured across ten observational plants to obtain reliable averages. Yield of red ripe fruit was computed by adding together the total fruit weight harvested at each picking. Pedicel length has been measured by using a digital Vernier calliper, and seed number was calculated by counting seeds from oven-dried fruits. Capsaicin content was assessed spectrophotometrically by following the standard post-harvest evaluation procedure. The addition of these diverse traits in Table 2 highlights the comprehensive nature of the study, ensuring that both yield-contributing and quality-related parameters were systematically measured to provide a robust basis for genetic variability and combining ability analysis.

Post-harvest fruit evaluation

During the post-harvest evaluation, capsaicin was calculated by using following method: Using spectrophotometric measurement, the capsaicin content in samples was determined following the method

recommended by (Sadasivam 1992). Chilli fruits were crushed and 0.5g powder of chilli was filled in test tube with ground-glass stopper of volumetric flask. Dry acetone of 10 ml was pipetted into flask and a mechanical shaker were used to agitate dry acetone for three hours. After agitation, the solution was centrifuged for ten minutes at 10,000 rpm or left to settle. Test tube was pipetted with 1ml clear supernatant and was dried in hot water bath. After dissolving the 5ml of a 0.4% sodium hydroxide, 3 ml 3% phosphomolybdic acid was added and after shaking the ingredients, they were left for an hour. After sudden result was purified into centrifuge tubes is to avoid floating debris, then centrifuged for ten to fifteen minutes at 500 rpm. The blue solution was arranged into the cuvette and the absorbance was measured at 650 nm. After running the test samples with a blank reagent, a standard graph was created.

The reagents:

- 3% phosphomolybdic acid
- 0.4% sodium hydroxide
- Dry acetone (25g anhydrous sodium sulphate was added to 500ml acetone one day prior to use)
- Capsaicin's stock standard solution [50mg capsaicin was taken then dissolved in 50ml 0.4% NaOH solution (1000µg/ ml)]. The Working standard [10ml of stock standard was diluted to 50ml with 0.4% NaOH solution (200µg/ ml)].

Standard graph preparation: A calibration curve was constructed using pure capsaicin in the range of 0-200 µg. Subsequently, aliquots of 0.2, 0.4, 0.6, 0.8 and 1.0 ml of the working standard solution were dispensed into fresh test tubes and processed following aforementioned protocol.

The capsaicin percentage was estimated using given formula:

$$\text{Capsaicin (\%)} = \frac{\mu\text{g capsaicin} \times 100 \times 100}{1000000 \times 1 \times 0.5}$$

Statistical analysis

The raw data for quantitative and qualitative was analysed for ANOVA (analysis of variance) at multi-location trial analyses were conducted using the R software (R Core Team 2024) and PBTools software (PBTools 2014). Whereas, figures were generated via. MS Excel and PAST software; version 4.15 (Hammer et al. 2001). The (ANOVA) analysis for individual and pooled environments was computed with R software (version 4.2.2).

Analysis of variance (ANOVA)

Variation's source	df	SS	MSS	VR
(r) Replication	(r-1)	(Sr)	$Sr/(r-1) = Mr$	Mr/Me
(g) Genotypes	(g-1)	(Sg)	$Sg/(g-1) = Mg$	Mg/Me
(e) Error	[(r-1) (g-1)]	(Se)	$Se/(r-1) (g-1) = Me$	

Where,

df = Degree of freedom

SS = Sum of squares

190	MSS	=	Mean sum of squares
191	VR	=	Variance ratio
192	r	=	replication's number
193	g	=	genotype's number
194	Sr	=	Replications SS
195	Sg	=	Genotypes SS
196	Se	=	Sum of squares (error)
197	Mr	=	Replications means sum of squares
198	Mg	=	Genotypes means sum of squares
199	Me	=	Means sum of squares (error)

200

201 The F-value obtained from the analysis was compared against the corresponding tabulated value. In cases where
 202 the F-test was significant, the critical difference (CD) was determined to evaluate the relative performance of
 203 individual entries. The standard error (SE) and CD were calculated using the following formulae:

204 $CD_{0.05} = S.E. (d) \times t (0.05) (r-1) (g-1) df$

205 $SE (d) \pm = \sqrt{\frac{2Me}{r}}$

206 $SE (m) \pm = \sqrt{\frac{Me}{r}}$

209 Where,

210 $CD_{0.05}$ = Critical difference at 5 % significance level

211 $SE (d) \pm$ = Standard error of difference

212 $SE (m) \pm$ = Mean standard error

213 Griffing's model-I with fixed effect and method-2 (Parents and one set of F_1 's without reciprocals)
 214 was used for analysis of combining ability (Griffing 1956). The experimental material was treated as a
 215 population from which inferences were drawn. The effects of combining ability of both hybrids and parents
 216 were examined by employing them as testers, thereby facilitating the identification of superior combiners.
 217 When the general combining ability and specific combining ability mean squares was identified as significant,
 218 assessment of SCA effects and GCA effects was computed for both ' $p(p-1)/2$ ' hybrids and 'p' parents,
 219 respectively. Heterosis magnitude had been calculated basis on data from different fruit quality and quantitative
 220 traits. It was presented as decrease or increase percentage in mean performance of F_1 over the better parent
 221 which is known as heterobeltiosis and standard variety which is known as standard/economic heterosis. The
 222 following formulas were applied to estimate heterosis:

223 ***Heterobeltiosis:***

224 It is determined by the difference between F_1 and the better parent (Fonseca 1968) and is computed by
 225 using following formula:

226 **Heterobeltiosis (%)** = $\frac{\overline{F_1} - \overline{BP}}{\overline{BP}} \times 100$

227 Where,

228 $\overline{F_1}$ = F_1 's mean performance

229 $\overline{BP}$ = Mean value of better parent of respective cross combination.

230

Standard heterosis:

$$\text{Standard heterosis (\%)} = \frac{\overline{F_1} - \overline{SC}}{\overline{SC}} \times 100$$

Where,

$\overline{F_1}$ = F_1 's mean performance

$\overline{SC}$ = Standard check's mean performance

Where, BP signifies better parent's mean value and SC signifies standard check's mean value

SE (Standard error) for pooled environment: $\pm \sqrt{(2Mc/rE)} = SE (H_2)$.

For assessment of the heterosis significance, 't' assessed economic value of heterosis were compared against tabulated values 't' at degree of freedom (error) at ($P \leq .05$). The findings were presented on basis of individual and pooled data whereas individual data is given on supplementary tables (Supplementary table S1, S2 & S3).

RESULTS

Analysis of variance for dialled design

Pooled ANOVA shown in the Table 3 indicated considerable variation among all the three environments for all traits studied. The sum of square's mean due to genotypes, parents and also hybrids were also considerably significant to every trait. Genotype $\times$ Environment interaction ($G \times E$) and Hybrids $\times$ Environments ($F_1 \times E$) showed statistically significance across the majority of traits studied, except pedicel length. Similarly, the Parents vs Hybrids (P vs F_1), the mean SS was considerably significant to all characters except capsaicin. The mean SS to Parents $\times$ Environments ($P \times E$), was notable significant only for red ripe fruit yield per plant, fruit weight and number of fruits per plant. Likewise, the mean SS to the (Parents vs Hybrids) $\times$ Environments (P vs F_1) $\times E$ has been found notable significant only for red ripe fruit yield per plant, number of seeds per fruit and number of fruits per plant.

Mean performance of Parents and F_1 Hybrids across three locations

Table 4a presents the mean performance of both the parental lines and F_1 hybrids for each studied trait. Fruit production per plant has always been a major determinant of overall productivity, is continuous to be a priority goal in chilli breeding programmes. A comprehensive examination of the data is presented in Table 4a across all settings presenting that in almost all cases, all the parents and hybrids, with the exception of Surajmukhi $\times$ Pusa Jwala, outperformed the check DKC-8 for red ripe fruit output per plant. Him Palam Mirch 2 was consistently the highest-ranking parent across all environments, with values of 473.72, 405.28, and 375.29 in E1, E1, and E3, respectively. The hybrids Him Palam Mirch 2 $\times$ Punjab Guchheddar showed the highest fruit yield per plant under E1 (699.96), E2 (596.07), and E3 (505.88), followed by Him Palam Mirch 2 $\times$ Pusa Sadabahar in E1 (619.96) and Him Palam Mirch 2 $\times$ Him Palam Mirch 1 in the E2 (594.05) and E3 (478.05). The hybrids were found significantly superior at $p < 0.05$. Data from multiple environments, pooled data showed that Him Palam Mirch 2 (418.10g) had highest red ripe fruit yield per plant, followed by Punjab Guchheddar (334.02g). In the hybrids, Him Palam Mirch 2 $\times$ Punjab Guchheddar (600.63g) has ranked first for fruit yield per plant, followed by Him Palam Mirch 2 $\times$ Him Palam Mirch 1 with 530.15 g and Him Palam Mirch 2 $\times$ DKC-8 with 498.59 g, while check DKC-8 yielded (220.23g).

Plant height is another critical trait because taller plants have a lower incidence of diseases like fruit rot in places with high rainfall. The majority of the hybrids and one parent (Punjab Guchhedar) were taller than the control (DKC-8) at all the sites. Punjab Guchhedar, Him Palam Mirch 2 $\times$ Pusa Sadabahar (93.46) in E1, Punjab Guchhedar $\times$ DKC-8 (85.16) in E2, Surajmukhi $\times$ Punjab Guchhedar (77.33) in E3, and Surajmukhi $\times$ Punjab Guchhedar (77.33) in E3 exhibited the highest plant height at all three locations and these were significantly superior ($p < 0.05$). Pooled across locations, all hybrids had significantly higher plant height than the control DKC-8 (68.14) (Fig. 2). Among parents, Punjab Guchhedar (70.86) had the highest plant height among parents, followed by the crosses, Him Palam Mirch 2 $\times$ DKC-8 (79.52) and Him Palam Mirch 2 $\times$ Pusa Sadabahar (78.12).

Fruit yield per plant in crops is significantly correlated with total number of fruits per plant as a direct contributor to increase fruit yield. The analysis of Table 4a revealed that among the parents, Pusa Jwala (127.33) has the highest number of fruits, followed by Punjab Guchhedar (127) and Him Palam Mirch 2 (126.33) in E1, Punjab Guchhedar (141.33) followed closely by Pusa Jwala (131.67) and Surajmukhi (122.33) in E2, and Punjab Guchhedar (122.30) followed closely by Pusa Jwala (122.17) and Him Palam Mirch 2 (111.47) in E3. Pusa Jwala $\times$ Punjab Guchhedar produced the highest number of fruits across environments under E1 (219.67), E2 (221), and E3 (210.07). Overall, both the parents and hybrids outperformed the check DKC-8 under all the three locations, with significant differences at $p < 0.05$. The pooled analysis across habitats revealed that superiority of Punjab Guchhedar (130.21) for maximum fruits number per plant, closely succeeded by Pusa Jwala (127.06) and Him Palam Mirch 2 (117.82) among parents. The hybrids Pusa Jwala $\times$ Punjab Guchhedar (216.19), Him Palam Mirch 2 $\times$ DKC-8 (180.63), and Pusa Sadabahar $\times$ DKC-8 (168.04) produced more fruits than the control (67.62) (Fig. 2), with a significant difference at $p < 0.05$.

Fruit weight trait is also a close contributor to increase fruit yield. The results showed that for fruit weight, Him Palam Mirch 2 had significantly higher fruit weight in E1 (3.76), E2 (3.50), and E3 (3.37) among parents than the control (DKC-8). Among the hybrids, Him Palam Mirch 2 $\times$ Pusa Sadabahar had the highest fruit weight in E1, E2, and E3, with values of 4.11, 4.37, and 3.98 g, respectively, followed closely by Him Palam Mirch 2 $\times$ Punjab Guchhedar in E1 (4.02) and E3 (3.63), and Him Palam Mirch 2 $\times$ Him Palam Mirch 1 in the E2 (4.00), which were found significantly superior at $p < 0.05$. Pooled over environments, one parent and four hybrids significantly surpassed the check DKC-8 (3.26) among which Him Palam Mirch 2 (3.54) showed maximum fruit weight and among hybrids Him Palam Mirch 2 $\times$ Pusa Sadabahar (4.16) showed maximum fruit weight closely followed by Him Palam Mirch 2 $\times$ Punjab Guchhedar (3.80) and Him Palam Mirch 2 $\times$ Him Palam Mirch 1 (3.78) and these were significantly superior at $p < 0.05$. Mean data for fruit weight across all the locations is presented in Table 4a.

Data In Table 4b indicates that among the parents Surajmukhi recorded the minimum pedicel length under all the environments with the values of 3.00, 3.07 and 3.01 in E1, E2 and E3 respectively. Among these hybrids, the least pedicel length was noted in Him Palam Mirch 2 $\times$ Punjab Guchhedar across environments, 2.77, 2.77 and 2.75 in E1, E2 and E3 respectively and closely followed by Surajmukhi $\times$ Pusa Jwala under E1 (3.00), E2 (3.07) and E3 (2.96). Pooled data analysis across environments showed that among parents Surajmukhi (3.03) had smallest pedicel length than the check DKC-8 (3.19). Among hybrids, six hybrids

showed minimum pedicel length than the check with Him Palam Mirch 2 × Punjab Guchhedar ranking first and closely followed by Surajmukhi Pusa × Jwala and Him Palam Mirch 2 × DKC-8 with having values 2.76, 3.01 and 3.07 successively and these outperformed others at $p < 0.05$ in the study.

With respect to the number of seeds per fruit, Pusa Jwala ranked first in each environment with having values 68.60, 69.53 and 66.07 in E1, E2 and E3 respectively and closely followed by Pusa Sadabahar in E1 (62.70), E2 (64.07) and E3 (60.00). Among hybrids, highest number of seeds per fruit were recorded by Him Palam Mirch 2 × Pusa Sadabahar (81.27) under E1 and E2 (70.80) and Punjab Guchhedar × DKC-8 (67.93) under E3 respectively. Pooled data over environments revealed that four parents and fifteen hybrids have highest number of seeds than the check DKC-8 (53.44) among which Him Palam Mirch 2 × Pusa Sadabahar (71.87) outyielded all other hybrids significantly and closely followed by Punjab Guchhedar × DKC-8 (62.58) and these were significantly superior at $p < 0.05$. Mean data for seed count per fruit across each location is displayed in the Table 4b.

Maximum capsaicin content was found in Pusa Jwala among the parents under all the environments with range E1 (0.35), E2 (0.36) and E3 (0.33) and closely followed by Punjab Guchhedar under E1 (0.32), E2 (0.32) and E3 (0.31). Highest capsaicin in hybrids was recorded by Pusa Jwala × Punjab Guchhedar (0.34) under E1 and (0.32) under E3 and Pusa Jwala × DKC-8 (0.35) under E2. Pooled results over environment, three parents and thirteen hybrids had higher capsaicin content than the check DKC-8 (0.26). The best parent was Pusa Jwala (0.35) and best hybrids for capsaicin content were Pusa Jwala × Punjab Guchhedar (0.32) and Pusa Jwala × DKC-8 (0.32) as presented in Table 4b.

Assessment of combining ability

Parental general combining ability effects

Estimation of general combining ability effects for all the parents at all the three locations and pooled are presented in Table 5a - Table 5b. Significant and favourable gca impacts for red ripe fruit yield per plant were observed in two parents in the E2 and E1, three parents in the E3 and the pooled environments. The parents viz. Him Palam Mirch 2 in E1 (136.72), E2 (76.98), E3 (72.57) and pooled (95.42); Punjab Guchhedar in E1 (51.23), E2 (57.38), E3 (50.93) and pooled (53.18); DKC-8 in E3 (6.59) and on basis of pooled environments (3.53) revealed significant & positive effects of gca for red ripe fruit yield per plant. On the basis of result these parents were evaluated as favorable good general combiners for red ripe fruit yield per plant. For plant height, parents viz., Him Palam Mirch 2 in E1 (4.98), in E2 (1.89) and pooled (2.38); Surajmukhi in E3 (3.21) and pooled (0.65); Punjab Guchhedar in E1 (2.89), E2 (3.65), E3 (3.30) and pooled (3.28); DKC-8 in E1 (1.89), E2 (3.24), E3 (2.99) and on pooled basis (2.71) revealed significant and the positive effects of gca and registered as good general combiners for plant height. For number of fruits per plant, three parents from E1 and E2 and four parents from E3 and pooled showed significant and beneficial gca effects. Three parents on pooled basis and in E1, E2, E3 showed substantial and beneficial gca impacts on number of fruits per plant. Among parents viz., Him Palam Mirch 2 in E1 (16.93), E2 (5.87), E3 (5.98) and pooled (9.59); Pusa Jwala in E1 (4.93), E2 (5.24), E3 (6.80) and pooled (5.66); Punjab Guchhedar in E1 (16.96), E2 (19.50), E3 (19.02) and pooled (18.49) showed significant and positive gca effects for number of fruits per plant. For fruit weight, three parents

in E1, E2, E3 and on pooled basis were registered as substantial and beneficial general combiners for fruit weight. Among parents viz., Him Palam Mirch 2 in E1 (0.65), E2 (0.48), E3 (0.52) and pooled (0.55); Punjab Guchhedar in E1 (0.06), E2 (0.05), E3 (0.05), pooled (0.05); DKC-8 in E1 (0.15), E2 (0.15), E3 (0.14) and on pooled basis (0.15) were found substantial and beneficial gca impacts for fruit weight and considered as good general combiners for fruit weight. The parents viz., Him Palam Mirch 1 in E1 (-0.25), E2 (-0.27), E3 (-0.26) and pooled (-0.26); Surajmukhi in E1 (-0.10), E2 (-0.08), E3 (-0.07) and pooled (-0.08); Pusa Jwala in E1 (-0.09), E2 (-0.10), E3 (-0.08) and on pooled basis (-0.09) showed the significant and desirable (negative) gca effects for pedicel length and registered as good general combiners. For pedicel length, three parents in E1, E2, E3 and pooled revealed significant and desired (negative) gca impacts. For number of seeds per fruit, three parents in E1 and on pooled basis, two parents in E2 and E3 had substantial and favorable gca impacts. Among parents viz., Him Palam Mirch 2 in E1 (4.12) and pooled (1.79); Pusa Jwala in E1 (4.27), E2 (3.10), E3 (3.02) and pooled (3.46); Pusa Sadabahar in E1 (1.69), E2 (3.03), E3 (1.07) and pooled basis (1.93) shown substantial and favorable gca impacts on number of seeds per fruit and were regarded as good general combiners. Significant and favorable gca impacts for capsaicin concentration were shown by 4 parents in E1, E3 and pooled basis and three parents in E2. Pusa Jwala in E1 (0.04), E2 (0.03), E3 (0.02) and pooled (0.03), Punjab Guchhedar in E1 (0.03), E2 (0.02), E3 (0.03) and pooled (0.02), Pusa Sadabahar (0.01) in E1, E2, E3 and pooled basis (0.01) and DKC-8 in E1 (0.01), E3 (0.01) and pooled basis (0.01) had significant and the positive gca effects for capsaicin content. Therefore, they were registered as better general combiners for capsaicin content.

Specific combining ability for F_{1s}

Specific combining ability effects for 21 hybrids across the environments evaluated for fruit yield and growth parameters are presented in Table 6a – Table 6b. The estimates of specific combining ability (SCA) for red ripe fruit yield per plant exhibited wide variations among the hybrids, ranging from -172.15 in Him Palam Mirch 2 $\times$ Pusa Jwala to 169.36 in Him Palam Mirch 2 $\times$ Punjab Guchhedar in E1, from -116.39 in Him Palam Mirch 2 $\times$ Pusa Jwala to 165.49 in Him Palam Mirch 2 $\times$ Him Palam Mirch 1 in the E2, from -106.19 in Him Palam Mirch 2 $\times$ Pusa Jwala to 141.70 in Pusa Sadabahar $\times$ DKC-8 in E3, and from -131.58 in Him Palam Mirch 2 $\times$ Pusa Jwala to 142.11 in Pusa Sadabahar $\times$ DKC-8 in pooled data and the significant and consistent performance of these hybrids registered themselves as good specific combiners. Out of 21 crosses, 9 in E1, 10 in E2, 10 in the E3 and 11 in the pooled environments revealed significant and the positive SCA effects. The significant and consistent performance of Him Palam Mirch 2 $\times$ Punjab Guchhedar in E1 (169.36), Him Palam Mirch 2 $\times$ Him Palam Mirch 1 in E2 (165.49), and Pusa Sadabahar $\times$ DKC-8 in E3 (141.70) and pooled data (142.11) registered these crosses as good specific combiners for red ripe fruit yield per plant (Fig. 3).

For plant height, SCA effects ranged from -4.63 in Pusa Jwala $\times$ Pusa Sadabahar to 17.96 in Him Palam Mirch 2 $\times$ Pusa Sadabahar in E1, from -4.96 in Him Palam Mirch 1 $\times$ Surajmukhi to 7.64 in Him Palam Mirch 2 $\times$ Him Palam Mirch 1 in E2, from -4.49 in Him Palam Mirch 1 $\times$ DKC-8 to 8.59 in Surajmukhi $\times$ Pusa Sadabahar in E3, and from -3.53 in Him Palam Mirch 1 $\times$ DKC-8 to 7.56 in Him Palam Mirch 2 $\times$ Pusa Sadabahar in pooled analysis. Out of 21 crosses, 6 in E1, 10 in E2, 7 in the E3 and 11 in the pooled environments, showed significant and positive effects of SCA. The SCA effects across all the environments are presented in Table 6a. The significant and consistent performance of Him Palam Mirch 2 $\times$ Pusa Sadabahar in E1, Him Palam Mirch 2 $\times$ Him Palam Mirch 1 in the E2, Surajmukhi $\times$ Pusa Sadabahar in E3, and Him Palam

Mirch 2 × Pusa Sadabahar in pooled analysis registered these crosses as good specific combiners for plant height.

For number of fruits per plant, SCA effects ranged from -40.06 in Him Palam Mirch 2 × Pusa Jwala to 75.91 in Pusa Jwala × Punjab Guchhedar in E1, from -32.47 in Surajmukhi × Pusa Sadabahar to 69.53 in Pusa Jwala × Punjab Guchhedar in E2, from -29.06 in Him Palam Mirch 2 × Pusa Jwala to 70.49 in Pusa Jwala × Punjab Guchhedar in E3, and from -33.77 in Him Palam Mirch 2 × Pusa Jwala to 71.98 in Pusa Jwala × Punjab Guchhedar in pooled analysis. Out of 21 crosses, 8 in E1, 10 in E2, 10 in the E3 and 9 in the pooled data revealed significant and desirable positive effects of SCA. The cross Pusa Jwala × Punjab Guchhedar were emerged as highest positive and good specific combiners across environments and number of fruits per plant under pooled environments. Data in Table 6a present the SCA effects for number of fruits per plant across all the locations.

For fruit weight, the SCA values ranged from -0.64 in Him Palam Mirch 2 × DKC-8 to 0.83 in Him Palam Mirch 2 × Pusa Sadabahar in E1, from -0.88 in Him Palam Mirch 2 × DKC-8 to 1.03 in Him Palam Mirch 2 × Pusa Sadabahar in E2, from -0.70 in Him Palam Mirch 2 × DKC-8 to 0.90 in Him Palam Mirch 2 × Pusa Sadabahar in E3, and from -0.74 in Him Palam Mirch 2 × DKC-8 to 0.92 in Him Palam Mirch 2 × Pusa Sadabahar in pooled analysis. Out of 21 crosses, 9 in E1, 7 in E2, 10 in E3, and 9 in pooled data had significant positive SCA effects. The cross Him Palam Mirch 2 × Pusa Sadabahar was emerged as consistent, highest positive and good specific combiner across environments and in pooled analysis for fruit weight (Fig. 3).

For pedicel length, SCA effects varied from -0.67 in Him Palam Mirch 2 × Punjab Guchhedar to 0.61 in Surajmukhi × DKC-8 in E1, from -0.69 in Him Palam Mirch 2 × Punjab Guchhedar to 0.61 in Surajmukhi × DKC-8 in E2, from -0.62 in Him Palam Mirch 2 × Punjab Guchhedar to 0.63 in Him Palam Mirch 2 × Pusa Sadabahar in E3, and from -0.66 in Him Palam Mirch 2 × Punjab Guchhedar to 0.59 in Him Palam Mirch 2 × Pusa Sadabahar in pooled analysis. Out of 21 crosses, 9 in E1, 9 in E2, 10 in E3, and 9 in pooled data showed significant desirable negative SCA effects. The cross Him Palam Mirch 2 × Punjab Guchhedar was emerged as highest negative and good specific combiner across environments and in pooled analysis by showing negative SCA effects for pedicel length.

For number of seeds per fruit, SCA effects ranged from -13.19 in Punjab Guchhedar × Pusa Sadabahar to 20.47 in Him Palam Mirch 2 × Pusa Sadabahar in E1, from -9.43 in Him Palam Mirch 1 × Surajmukhi to 8.32 in Him Palam Mirch 2 × Pusa Sadabahar in E2, from -11.18 in Punjab Guchhedar × Pusa Sadabahar to 14.19 in Punjab Guchhedar × DKC-8 in E3, and from -9.66 in Punjab Guchhedar × Pusa Sadabahar to 12.30 in Him Palam Mirch 2 × Pusa Sadabahar in pooled analysis. SCA effects for number of seeds per fruit is displayed in Table 6b. Out of 21 crosses, 6 in E1, 4 in E2, 4 in the E3 and 6 in pooled environments revealed positive and significant effects of SCA. The hybrids, Him Palam Mirch 2 × Pusa Sadabahar in E1, E2, and pooled analysis, while Punjab Guchhedar × DKC-8 in E3 were emerged as consistent and good specific combiner for number of seeds per fruit.

The superior crosses based on SCA effects for capsaicin are presented in Table 6b. SCA effects ranged from -0.04 in Him Palam Mirch 1 × Pusa Jwala to 0.04 in Him Palam Mirch 2 × Pusa Jwala in E1, from -0.04 in Pusa Jwala × Punjab Guchhedar to 0.03 in Pusa Jwala × DKC-8 in E2, from -0.02 in Him Palam Mirch 1 × Pusa Jwala to 0.04 in Him Palam Mirch 1 × DKC-8 in E3, and from -0.03 in Him Palam Mirch 1 × Pusa Jwala to 0.02 in Him Palam Mirch 1 × DKC-8 in pooled analysis. Out of 21 crosses, 4 in E1, 4 in E2, 3 in the E3 and 7 in

the pooled environment revealed significant & desirable positive effects of SCA. The crosses, Him Palam Mirch 2 × Pusa Jwala in E1, Pusa Jwala × DKC-8 in E2, and Him Palam Mirch 1 × DKC-8 in E3 and pooled analysis were emerged as consistent and good specific combiner for capsaicin content.

Heterosis

Fruit yield is a major economic trait in chilli, and its improvement remains a central goal in breeding programmes. The better parent and standard heterosis for each trait is summarized in Table 7a – Table 7d. In the present study, heterosis for fruit yield per plant showed marked variation across environments. Heterobeltiosis ranged from -42.49% in P1 × P4 to 98.18% in P6 × P7 in E1, from -31.54% in P3 × P4 to 85.49% in P6 × P7 in E2, and from -36.65% in P3 × P4 to 112.08% in P6 × P7 in E3. Twelve hybrids under environment E1, ten under E2, and thirteen under E3 unveiled significant positive better parent heterosis over their respective parents. Among the crosses, P6 × P7 ranked first in all three environments, followed closely by P4 × P5 and P1 × P5 under E1, P1 × P5 and P1 × P2 under E2, and P4 × P5 and P5 × P7 under E3 environments. In pooled analysis, better parent heterosis ranged from -34.26% in P3 × P4 to 97.14% in P6 × P7, with P6 × P7 showing the highest desirable heterosis, closely followed by P1 × P5. This consistent performance of these hybrids across environments ranking them first for improving fruit yield is presented in Table 7b. Standard heterosis also showed wide variations for fruit yield per plant and showed ranges from -22.55% in P3 × P6 to 223.53% in P1 × P5 in E1, from -12.19% in P3 × P6 to 135.81% in P1 × P5 in E2, and from -4.65% in P3 × P4 to 164.08% in P1 × P5 in the E3. The eighteen hybrids in E1, nineteen in E2 and the nineteen in E3 documented significant positive standard heterosis over the check P7. The most promising hybrids were P1 × P5, P1 × P6, and P1 × P7 in E1; P1 × P5, P1 × P2, and P5 × P7 in E2; and P1 × P5, P1 × P2, and P1 × P7 in E3. On pooled basis, P1 × P5 showed the highest standard heterosis, followed by P1 × P2, indicating strong yield advantage over the standard check.

Increase in plant height over the better parent ranged from -14.68% in Pusa Jwala × Pusa Sadabahar to 37.24% in Him Palam Mirch 2 × Pusa Sadabahar in E1, from -17.77% in Pusa Jwala × Punjab Guchhedar to 15.51% in Him Palam Mirch 2 × Him Palam Mirch 1 in the E2 and from -14.99% in Pusa Jwala × Pusa Sadabahar to 24.62% in Him Palam Mirch 1 × Surajmukhi in the E3. Seven hybrids under E1, nine under E2, and eight under E3 environments revealed positive & significant heterobeltiosis for plant height. The highest desirable heterobeltiosis was recorded by Him Palam Mirch 2 × Pusa Sadabahar in E1 (37.24%), Him Palam Mirch 2 × Him Palam Mirch 1 in E2 (15.51%) and Him Palam Mirch 1 × Surajmukhi in E3 (24.62%) which makes these crosses ranking first for improving plant height. In pooled analysis, heterobeltiosis ranged from -14.57% in Pusa Jwala × Punjab Guchhedar to 18.89% in Him Palam Mirch 2 × Pusa Sadabahar and closely followed by Him Palam Mirch 2 × Him Palam Mirch 1 (16.73%). The top ranked hybrids based on high heterosis effects are presented in Table 7a. These results indicate that these hybrids performed better than their better parents and ranked first for plant height. Economic heterosis over the standard check DKC-8 was significant for eight, nine, and nine crosses in E1, E2, and E3, respectively, in the desirable direction. Standard heterosis ranged from -17.44% in Pusa Jwala × Pusa Sadabahar to 35.01% in Him Palam Mirch 2 × Pusa Sadabahar in E1, from -15.52% in Pusa Jwala × Pusa Sadabahar to 18.28% in Punjab Guchhedar × DKC-8 in E2, and from -19.12% in Pusa Jwala × Pusa Sadabahar to 22.34% in Surajmukhi × Punjab Guchhedar in E3. The highest positive standard heterosis was possessed by Him Palam Mirch 2 × Pusa Sadabahar under E1 (35.01%), Punjab Guchhedar × DKC-8 under E2 (18.28%), and Surajmukhi × Punjab Guchhedar under E3

(22.34%) environments. Pooled data represented that, Punjab Guchhedar $\times$ DKC-8 showed the highest significant positive standard heterosis at 18.42%, closely followed by Him Palam Mirch 2 $\times$ DKC-8 at 16.69% and emerged as best hybrids for plant height.

Heterobeltiosis for number of fruits per plant ranged from -37.77% in Surajmukhi $\times$ Pusa Sadabahar to 72.51% in Pusa Jwala $\times$ Punjab Guchhedar under E1, from -40.87% in Surajmukhi $\times$ Pusa Sadabahar to 57.35% in Him Palam Mirch 2 $\times$ DKC-8 under E2, and from -37.74% in Surajmukhi $\times$ Pusa Sadabahar to 77.09% in Pusa Sadabahar $\times$ DKC-8 under E3. Eight hybrids in the E1, six in the E2 and nine in the E3 showed positive and significant heterobeltiosis over their parents. The top-performing crosses were Pusa Jwala $\times$ Punjab Guchhedar, Pusa Sadabahar $\times$ DKC-8, and Him Palam Mirch 2 $\times$ DKC-8 in E1; Him Palam Mirch 2 $\times$ DKC-8, Pusa Sadabahar $\times$ DKC-8, and Pusa Jwala $\times$ Punjab Guchhedar in E2; and Pusa Sadabahar $\times$ DKC-8, Pusa Jwala $\times$ Punjab Guchhedar, and Him Palam Mirch 2 $\times$ DKC-8 in E3. The results showed by pooled analysis revealed that heterobeltiosis varied from -38.91% in Surajmukhi $\times$ Pusa Sadabahar to 66.58% in Pusa Jwala $\times$ Punjab Guchhedar crosses. The consistent and better performance was shown by Pusa Jwala $\times$ Punjab Guchhedar at 66.57%, followed by Pusa Sadabahar $\times$ DKC-8 at 66.58% across all the environments which gives these crosses first ranking for improving number of fruits per plant. Standard heterosis for number of fruits per plant ranged from 0.50% in Surajmukhi $\times$ Pusa Sadabahar to 229.50% in Pusa Jwala $\times$ Punjab Guchhedar in E1, from -2.69% in Surajmukhi $\times$ Pusa Sadabahar to 197.31% in Pusa Jwala $\times$ Punjab Guchhedar in E2, and from -0.17% in Surajmukhi $\times$ Pusa Sadabahar to 239.58% in Pusa Jwala $\times$ Punjab Guchhedar in E3. Twenty hybrids in each of E1, E2, and E3 showed positive & significant standard heterosis over the check DKC-8. The best crosses were Pusa Jwala $\times$ Punjab Guchhedar, Him Palam Mirch 2 $\times$ DKC-8 and the Him Palam Mirch 2 $\times$ Punjab Guchhedar in E1; Pusa Jwala $\times$ Punjab Guchhedar, Him Palam Mirch 2 $\times$ DKC-8, and Pusa Sadabahar $\times$ DKC-8 in E2; and Pusa Jwala $\times$ Punjab Guchhedar, Him Palam Mirch 2 $\times$ DKC-8, and Pusa Sadabahar $\times$ DKC-8 in E3. Across pooled data, Pusa Jwala $\times$ Punjab Guchhedar showed the highest positive & significant standard heterosis at 220.78%, followed by Him Palam Mirch 2 $\times$ DKC-8 at 167.13% for number of fruits per plant.

For average fruit weight, heterobeltiosis ranged from -30.35% in Him Palam Mirch 2 $\times$ Pusa Jwala to 22.30% in Him Palam Mirch 1 $\times$ Pusa Sadabahar under E1, from -22.88% in Him Palam Mirch 2 $\times$ DKC-8 to 25.07% in Him Palam Mirch 2 $\times$ Pusa Sadabahar under E2, and from -24.26% in Him Palam Mirch 2 $\times$ Pusa Jwala to 23.39% in Him Palam Mirch 1 $\times$ Pusa Sadabahar under E3 environments (Table 7c). Six hybrids in E1, seven in E2, and seven in E3 showed significant positive heterobeltiosis over their parents. The crosses Him Palam Mirch 1 $\times$ Pusa Sadabahar, Him Palam Mirch 1 $\times$ Punjab Guchhedar, and Him Palam Mirch 2 $\times$ Pusa Sadabahar showed the highest desirable heterobeltiosis in E1; Him Palam Mirch 2 $\times$ Pusa Sadabahar, Him Palam Mirch 1 $\times$ Pusa Sadabahar, and Him Palam Mirch 2 $\times$ Him Palam Mirch 1 in E2; and Him Palam Mirch 1 $\times$ Pusa Sadabahar, Him Palam Mirch 2 $\times$ Pusa Sadabahar, and Surajmukhi $\times$ Punjab Guchhedar in E3. In pooled analysis, heterobeltiosis varied from -24.51% in Him Palam Mirch 2 $\times$ Pusa Jwala to 21.91% in Him Palam Mirch 1 $\times$ Pusa Sadabahar. The highest significant positive heterobeltiosis was recorded by Him Palam Mirch 1 $\times$ Pusa Sadabahar at 21.91%, followed by Him Palam Mirch 2 $\times$ Pusa Sadabahar at 17.42%. Standard heterosis for this trait ranged from -33.82% in Surajmukhi $\times$ Pusa Sadabahar to 28.01% in Him Palam Mirch 2 $\times$ Pusa Sadabahar under E1, from -32.31% in Pusa Jwala $\times$ Punjab Guchhedar to 25.79% in Him Palam Mirch 2 $\times$ Pusa Sadabahar under E2, and from -33.05% in Pusa Jwala $\times$ Punjab Guchhedar to 28.63% in Him Palam Mirch 2 $\times$ Pusa Sadabahar under E3 environments. Four hybrids in each of E1, E2, and E3 showed significant positive

standard heterosis over the check DKC-8. The crosses performed best and emerged as best hybrids were Him Palam Mirch 2 × Pusa Sadabahar, Him Palam Mirch 2 × Punjab Guchhedar, and Him Palam Mirch 2 × Him Palam Mirch 1 under E1; Him Palam Mirch 2 × Pusa Sadabahar, Him Palam Mirch 2 × Him Palam Mirch 1, and Him Palam Mirch 2 × Punjab Guchhedar under E2; and Him Palam Mirch 2 × Pusa Sadabahar, Him Palam Mirch 2 × Punjab Guchhedar, and Him Palam Mirch 2 × Him Palam Mirch 1 under E3 environments. Across pooled data, Him Palam Mirch 2 × Pusa Sadabahar showed the highest significant positive standard heterosis at 27.42% and closely followed by Him Palam Mirch 2 × Punjab Guchhedar at 16.49% which indicates best performance of these hybrids to improve fruit weight.

For pedicel length, negative heterosis is considered desirable. Heterobeltiosis ranged from -31.32% in Him Palam Mirch 2 × Punjab Guchhedar to 27.11% in Surajmukhi × DKC-8 in E1, from -31.30% in Him Palam Mirch 2 × Punjab Guchhedar to 28.87% in Surajmukhi × DKC-8 in E2, and from -31.08% in Him Palam Mirch 2 × Punjab Guchhedar to 29.03% in Surajmukhi × DKC-8 in E3. Eleven hybrids in E1, ten in E2, and ten in E3 showed significant negative heterobeltiosis over their parents. The best crosses in the desirable direction were Him Palam Mirch 2 × Punjab Guchhedar, Surajmukhi × Pusa Jwala, and Him Palam Mirch 2 × Pusa Jwala under E1; Him Palam Mirch 2 × Punjab Guchhedar, Surajmukhi × Pusa Jwala, and Him Palam Mirch 2 × Pusa Jwala under E2; and Him Palam Mirch 2 × Punjab Guchhedar, Surajmukhi × Pusa Jwala, and Him Palam Mirch 2 × Pusa Jwala under E3 environments. In pooled analysis, heterobeltiosis ranged from -31.27% in Him Palam Mirch 2 × Punjab Guchhedar to 28.33% in Surajmukhi × DKC-8. The hybrids which showed highest desirable negative heterobeltiosis and ranked first are Him Palam Mirch 2 × Punjab Guchhedar at -31.27%, followed by Surajmukhi × Pusa Jwala at -25.61% for improving this trait. Standard heterosis over the check DKC-8 was significant for two crosses under E1, one under E2, and two under E3 environments in the desirable negative direction. Standard heterosis ranged from -14.33% in Him Palam Mirch 2 × Punjab Guchhedar to 33.61% in Him Palam Mirch 1 × Pusa Sadabahar under E1, from -14.43% in Him Palam Mirch 2 × Punjab Guchhedar to 37.11% in Him Palam Mirch 1 × Pusa Sadabahar under E2, and from -11.29% in Him Palam Mirch 2 × Punjab Guchhedar to 29.03% in Surajmukhi × DKC-8 under E3 environments. The most desirable standard heterosis was shown by Him Palam Mirch 2 × Punjab Guchhedar in all three environments, followed by Surajmukhi × Pusa Jwala and Him Palam Mirch 2 × DKC-8. Across pooled data, Him Palam Mirch 2 × Punjab Guchhedar showed the highest significant negative standard heterosis at -13.38%, closely followed by Surajmukhi × Pusa Jwala at -5.68% which indicates best performance of these hybrids to reduce pedicel length.

For number of seeds per fruit, heterobeltiosis among the hybrids ranged from -36.20% in Surajmukhi × Pusa Sadabahar to 29.61% in Him Palam Mirch 2 × Pusa Sadabahar under E1, from -22.67% in Him Palam Mirch 1 × Surajmukhi to 12.53% in Him Palam Mirch 2 × Him Palam Mirch 1 under E2, and from -26.44% in Punjab Guchhedar × Pusa Sadabahar to 24.12% in Punjab Guchhedar × DKC-8 under E3. These hybrids were registered as consistent and superior hybrids for number of seeds per fruit. Only one hybrid in E1, four in E2, and two in E3 showed significant positive heterobeltiosis over their parents. The best performing crosses in the desirable direction were Him Palam Mirch 2 × Pusa Sadabahar, Him Palam Mirch 2 × Punjab Guchhedar, and Him Palam Mirch 2 × Him Palam Mirch 1 under E1; Him Palam Mirch 2 × Him Palam Mirch 1, Punjab Guchhedar × DKC-8, and Him Palam Mirch 2 × Pusa Sadabahar under E2; and Punjab Guchhedar × DKC-8, Him Palam Mirch 2 × Him Palam Mirch 1, and Him Palam Mirch 2 × Pusa Sadabahar under E3 environments. In pooled analysis, heterobeltiosis ranged from -24.83% in Punjab Guchhedar × Pusa Sadabahar to 15.44% in

Him Palam Mirch 2 × Pusa Sadabahar. The highest significant positive heterobeltiosis was recorded by Him Palam Mirch 2 × Pusa Sadabahar at 15.44% and followed closely by Him Palam Mirch 2 × Him Palam Mirch 1 at 11.03%. Standard heterosis for number of seeds per fruit ranged from -25.41% in Him Palam Mirch 1 × Punjab Guchhedar to 52.57% in Him Palam Mirch 2 × Pusa Sadabahar under E1, from -23.58% in Palam Mirch × Surajmukhi to 25.24% in Him Palam Mirch 2 × Pusa Sadabahar under E2, and from -12.66% in Punjab Guchhedar × Pusa Sadabahar to 34.43% in Punjab Guchhedar × DKC-8 under E3 environments. Four hybrids in E1, seven in E2, and seven in E3 showed significant positive standard heterosis over the check DKC-8. The top and consistent crosses were Him Palam Mirch 2 × Pusa Sadabahar, Him Palam Mirch 2 × Punjab Guchhedar, and Pusa Jwala × Punjab Guchhedar in E1; Him Palam Mirch 2 × Pusa Sadabahar, Punjab Guchhedar × DKC-8, and Him Palam Mirch 2 × Him Palam Mirch 1 in E2; and Punjab Guchhedar × DKC-8, Him Palam Mirch 2 × Pusa Sadabahar, and Him Palam Mirch 1 × Pusa Sadabahar in E3. Across pooled data, Him Palam Mirch 2 × Pusa Sadabahar showed the highest significant positive standard heterosis at 34.47% and closely followed by Punjab Guchhedar × DKC-8 at 17.09% for number of seeds per fruit.

For capsaicin content, heterobeltiosis ranged from -34.29% in Him Palam Mirch 1 × Pusa Jwala to 7.69% in Surajmukhi × DKC-8 under E1, from -29.36% in Him Palam Mirch 1 × Pusa Jwala to 6.85% in Him Palam Mirch 1 × Surajmukhi under E2, and from -26.26% in Him Palam Mirch 1 × Pusa Jwala to 13.16% in Him Palam Mirch 1 × DKC-8 under E3 environments. One hybrid under E1 and two hybrids under E3 environments showed significant positive heterobeltiosis for capsaicin content and registered as superior hybrids, while no hybrid showed positive significance in E2. The best crosses in the desirable direction were Surajmukhi × DKC-8 and Him Palam Mirch 1 × DKC-8 in E1; Him Palam Mirch 1 × Surajmukhi, Him Palam Mirch 1 × DKC-8, and Surajmukhi × DKC-8 in E2; and Him Palam Mirch 1 × DKC-8, Him Palam Mirch 1 × Surajmukhi, and Surajmukhi × DKC-8 in E3. In pooled analysis, heterobeltiosis varied from -30.03% in Him Palam Mirch 1 × Pusa Jwala to 6.01% in Him Palam Mirch 1 × DKC-8. The crosses performed consistently and significantly for heterobeltiosis are recorded by Him Palam Mirch 1 × DKC-8 at 6.01%, followed closely by Surajmukhi × DKC-8 at 3.43% (Fig. 4). Standard heterosis for capsaicin content ranged from -28.21% in Him Palam Mirch 2 × Him Palam Mirch 1 to 30.77% in Pusa Jwala × Punjab Guchhedar in E1, from -11.39% in Him Palam Mirch 2 × Him Palam Mirch 1 to 31.65% in Pusa Jwala × DKC-8 in E2, and from -21.05% in Him Palam Mirch 2 × Him Palam Mirch 1 to 25.00% in Pusa Jwala × Punjab Guchhedar in E3. Nine hybrids in E1, ten in E2, and eight in E3 showed significant positive standard heterosis over the check DKC-8. The top crosses were Pusa Jwala × Punjab Guchhedar, Pusa Jwala × DKC-8, and Him Palam Mirch 2 × Pusa Jwala in E1; Pusa Jwala × DKC-8, Punjab Guchhedar × DKC-8, and Pusa Jwala × Pusa Sadabahar in E2; and Pusa Jwala × Punjab Guchhedar, Pusa Jwala × Pusa Sadabahar, and Surajmukhi × Punjab Guchhedar in E3. Across pooled data, Pusa Jwala × Punjab Guchhedar showed the highest significant positive standard heterosis at 22.32%, closely followed by Pusa Jwala × DKC-8 at 21.89% by performing consistently and improving capsaicin content.

Correlation association of economic heterosis to related traits

The association of heterosis among traits revealed a significant correlation between number of seeds per fruit and fruit weight. Red ripe fruit yield per plant was positively correlated with plant height, number of fruits per plant, fruit weight and number of seeds per fruit. Additionally, fruit weight was also positively correlated with plant height. (Fig. 5).

Association between per se performance, GCA, SCA and Heterosis

Pearson's correlation coefficient of SCA with economic heterosis and F_1 performance was significantly and positively associated for most of the characters (except capsaicin content for SCA- F_1 and SCA-EH). A significant and positive association was noticed between standard heterosis with F_1 for all the characters and presented in Table 8.

DISCUSSION

Open-pollinated varieties remain vital in hybridization programmes as they conserve broad genetic variability, serving as a foundation for recurrent selection, heterotic pool formation and parent identification (Santos Junior et al. 2023; Labroo et al. 2021; Shelton and Tracy 2015). The present experiment confirmed their utility by finding parents with high general combining ability (GCA) and hybrids with strong specific combining ability (SCA). Steady with earlier studies, heterosis breeding in chilli has proven an effective approach for enhancing potential of yield and uniformity, thus supporting global export opportunities. However, our results extend preceding findings by demonstrating that heterosis alone cannot determine hybrid superiority; per se performance and stability across environments should also be taken into consideration (Dod et al. 1992). Multi-location evaluation of the genotypes revealed significant differences in parental and hybrid performance, defining genetic diversity among the parents. Hybrids viz., *Him Palam Mirch 2* $\times$ *Punjab Guchhedar* (600.63 g), *Him Palam Mirch 2* $\times$ *Him Palam Mirch 1* (530.15 g), and *Pusa Jwala* $\times$ *Punjab Guchhedar* (474.24 g) significantly outperformed the standard check *DKC-8* (220.23 g) in mean performance. These findings not only support earlier studies on the importance of open-pollinated varieties but also emphasize the superiority of specific cross combinations under diverse Himalayan agro-climatic environments, thereby strengthening their potential for commercial cultivation and income enhancement for farmers. Comparable differences in mean performance among both hybrids and parental lines have been reported earlier by (Dhaliwal et al. 2014; Janaki et al. 2017; Negi 2018; Azadani 2020). These studies highlighted the role of genetic diversity in improving heterosis and combining ability are in agreement with the present studies. However, the magnitude of heterotic response observed in our material, particularly for red ripe fruit yield (>500 g plant⁻¹ in *Him Palam Mirch 2* $\times$ *Punjab Guchhedar* and *Pusa Jwala* $\times$ *Punjab Guchhedar*), exceeded the values reported in preceding studies, suggesting broader parental divergence and superior genetic complementarity. Unlike the single-location evaluations of preceding experiments, the present experiment of multi-environment evaluation across three Himalayan agro-climatic zones provided stronger evidence of stability and adaptability of the genotypes. This strengthens the importance of evaluating mean performance, GCA and SCA effects to find hybrids with both high yield potential and environmental resilience.

The superior fruit yield of the above-mentioned genotypes was largely correlated to higher performance for other traits such as plant height, number of fruits per plant, fruit weight, and thousand seed weight, that consistently contribute to improved red ripe fruit yield and raised capsaicin content for processing purpose (Meena et al. 2020). Comparable associations between plant height and genetic background were reported previously by Rohini et al. (2017), while Nasabiyera et al. (2013) highlighted the straight impact of branching on fruit number and yield per unit area. In addition to yield characters, industrial processing traits like pedicel length are critical, as longer pedicels increase labour costs while reducing powder quality. Lata and

Sharma (2024) highlighted the necessity for lines with shorter pedicels to minimize industrial expenses and improve product quality. In the present study, genotypes viz., *Him Palam Mirch 2* $\times$ *Punjab Guchhedar* (2.76 cm), *Surajmukhi Pusa* $\times$ *Jwala* (3.01 cm), and *Him Palam Mirch 2* $\times$ *DKC-8* (3.07 cm) exhibited minimum pedicel length, thereby aligning with industrial necessities and offering dual rewards of high yield while reducing processing cost. This data extends earlier reports by proving that yield superiority in chilli hybrids can be simultaneously combined with traits of industrial relevance, strengthening their potential for both cultivation and processing areas.

Pungency remains a major quality character in chilli, important for both industrial processing and fresh consumption purpose (Zaki et al. 2013). Capsanthin, the natural red pigment, has additional economic importance in cosmetics and pharmaceuticals (Rao et al. 2016). Capsaicin, the principal pungent alkaloid compound which chiefly contribute into pungency is located in the placenta and widely acknowledged for its medicinal properties including anti-inflammatory, analgesic, and antimicrobial properties (Fattori et al. 2016). In the present study, genotypes viz., *Pusa Jwala* $\times$ *DKC-8* (0.35%), *Pusa Jwala* $\times$ *Punjab Guchhedar* (0.34%), and *Pusa Jwala* $\times$ *DKC-8* (0.32%) recorded higher capsaicin content compared to the standard check *DKC-8* (0.26%). These findings are in accordance with earlier reports that highlighted the genetic basis of variation in pungency, but the magnitude of improvement observed here suggests superior parental divergence and effective heterotic combinations. Unlike previous studies that primarily showed pigment or pungency traits in isolation, our results validate the simultaneous enhancement of capsaicin content along with yield, thereby strengthening the potential of these genotypes for dual exploitation in processing and pharmaceutical industries.

Combining ability analysis is one of the most effective methods for identifying suitable parents, either to exploit heterosis or to accumulate desirable alleles (Begna 2021). It also delivers insights into the genetic control of key traits, thus enabling breeders to design efficient strategies for germplasm advancement (Fasahat et al. 2016). In line with prior reports (Meena et al. 2020), the present study identified *Him Palam Mirch 2*, *Punjab Guchhedar* and *DKC-8* as superior general combiners (GCA) for red ripe fruit yield and related attributes across environments, revealing their potential as parental lines in heterosis breeding. Comparable GCA effects were earlier reported in chilli by Vera-Guzmán et al. (2011), Jagtap et al. (2015), Kaur et al. (2017) and Shumbulo et al. (2018), although the magnitude of effects observed in our material was comparatively higher, suggesting broader genetic divergence among the selected parents. Additionally, hybrids derived from *Pusa Jwala*, *Punjab Guchhedar* and *DKC-8* demonstrated significant GCA effects for capsaicin content, thereby offering dual value as sources of pungency for industrial exploitation and as donors in breeding programmes. These findings are in accordance with earlier studies that demonstrated yield-related GCA can be simultaneously combined with quality traits such as capsaicin, strengthening the potential of identified parents and hybrids for both commercial cultivation and pharmaceutical purpose.

SCA effects are broadly recognized as predictors of heterosis, as non-fixable gene actions such as dominance and epistasis contribute to hybrid vigour (Chakrabarty et al. 2017). In the current study, top-ranked hybrids for yield per plant also presented significant and positive SCA effects for key traits: number of fruits per plant (*Pusa Sadabahar* $\times$ *DKC-8*), fruit weight and seed number (*Him Palam Mirch 2* $\times$ *Him Palam Mirch 1*), and pedicel length (*Him Palam Mirch 2* $\times$ *Punjab Guchhedar*). Across all the three environments, nine hybrids

under E1, ten under E2 and E3, and eleven under pooled analysis exhibited significant positive SCA effects for red ripe fruit yield, confirming the robustness of these combinations. Hybrids originated from good $\times$ good general combiners (*Him Palam Mirch 2* $\times$ *Punjab Guchhedar*, *Him Palam Mirch 2* $\times$ *DKC-8*, *Punjab Guchhedar* $\times$ *DKC-8*) are mainly promising for finding transgressive segregants in early generations, while crosses involving one good and one poor combiner (*Him Palam Mirch 2* $\times$ *Him Palam Mirch 1*, *Pusa Jwala* $\times$ *Punjab Guchhedar*, *Pusa Sadabahar* $\times$ *DKC-8*) may yield transgressive segregants in further advanced generations. For capsaicin content, hybrids such as *Him Palam Mirch 2* $\times$ *Pusa Jwala*, *Him Palam Mirch 1* $\times$ *Pusa Sadabahar* and *Him Palam Mirch 1* $\times$ *DKC-8* showed significant positive SCA effects, with parental lines (*Pusa Jwala*, *Pusa Sadabahar*, *DKC-8*) also presenting positive GCA effects. The occurrence of high SCA effects from poor $\times$ poor combiners indicate epistatic interactions, in accordance with Sharma et al. (2007) and highlights the potential of reciprocal recurrent selection or biparental mating to further use these combinations for desirable attributes.

Heterosis breeding continues to be an effective strategy for enhancing productivity in chilli, particularly when genetically diverse open-pollinated varieties are retained (Santos Junior et al. 2023; Labroo et al. 2021). In the current study, hybrids expressed standard heterosis for red ripe fruit yield ranging from -34.26% to 97.14% and economic heterosis from -12.51% to 172.73%. Such wide difference reflects the differential genetic diversity among parental combinations, supported by earlier observations (Shreshtha et al. 2011). Top ranked crosses viz., *Him Palam Mirch 2* $\times$ *Punjab Guchhedar* (172.73%), *Him Palam Mirch 2* $\times$ *Him Palam Mirch 1* (140.73%), and *Punjab Guchhedar* $\times$ *DKC-8* (116.24%) showed highest heterosis for fruit yield, confirming the role of component traits such as fruit weight, plant height, fruit number, and seed number in determining economic heterosis (Lata et al. 2023). Particularly, two hybrids also showed significant negative heterosis for pedicel length, indicating their importance for industrial processing where short pedicels reduce labour costs and improve product quality. Furthermore, two hybrids among top five high-yielding hybrids demonstrated maximum heterosis for capsaicin content, extending preceding reports by linking heterotic response not only to yield but also to quality traits of pharmaceutical and industrial significance. These findings highlight that heterosis breeding in chilli can simultaneously deliver hybrids with superior yield stability, while reducing processing costs, and enhanced capsaicin concentration, thereby strengthening their commercial potential.

A hybrid combination is generally considered best when high SCA is correlated with at least one parent showing favorable GCA effects, confirming the predictive value of SCA for heterosis (Marchesan et al. 2009; Singathiya et al. 2026). In the present experiment, a significant positive correlation is observed between SCA and economic heterosis among all traits, validating the role of non-additive gene action in heterosis expression (Meera et al. 2026; Yu et al. 2020). Thus, significance of SCA as a reliable indicator for predicting hybrid performance is supported by his consistent association. The strong correlation observed here is in accordance with preceding studies (Singathiya et al. 2026; Yu et al. 2020; Liu et al. 2021), which highlighted that hybrids with desirable heterosis often display significant SCA effects. Ten F₁ hybrids, including *Him Palam Mirch 2* $\times$ *Punjab Guchhedar*, *Pusa Sadabahar* $\times$ *DKC-8*, *Him Palam Mirch 2* $\times$ *Him Palam Mirch 1* and *Pusa Jwala* $\times$ *Punjab Guchhedar*, were isolated based on high per se values, high SCA effects, and significant heterosis. These results extend earlier outcomes by demonstrating that simultaneous evaluation of SCA, GCA and heterosis provides a robust framework for identifying promising hybrids with dual utility in yield enhancement and value-added spice production.

CONCLUSION

Heterosis breeding offers strong potential to improve both fresh and dry yield, yet the availability of F_1 chilli hybrids suitable for processing remains limited. Multi-location evaluation of heterosis, mean performance, GCA, and SCA enables identification of superior genotypes with stable performance across diverse environments. Commercial adoption of such hybrids can enhance productivity and quality, while combining ability analysis guides parent selection and breeding strategies for effective improvement of red ripe fruit yield and industrially important traits such as capsaicin. Superior genotypes identified in this study; Him Palam Mirch 2 $\times$ Punjab Guchhedar, Pusa Sadabahar $\times$ DKC-8, Him Palam Mirch 2 $\times$ Him Palam Mirch 1, Pusa Jwala $\times$ Punjab Guchhedar, Him Palam Mirch 2 $\times$ Pusa Jwala, Him Palam Mirch 2 $\times$ DKC-8, Pusa Jwala $\times$ DKC-8, Surajmukhi $\times$ Pusa Sadabahar, Him Palam Mirch 1 $\times$ DKC-8 and Him Palam Mirch 2 $\times$ Pusa Sadabahar demonstrated consistent superiority across locations. Beyond conventional outcomes, this research advances knowledge by linking heterosis and combining ability with adaptability under Himalayan agro-climatic conditions, while highlighting dual-purpose utility for spice and pharmaceutical industries. The correlation of SCA with economic heterosis provides a predictive framework for hybrid performance offering breeders novel tools for climate-resilient and value-added chilli improvement programmes.

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AUTHOR CONTRIBUTION

Conceptualization: AC, HDS; Methodology: AC, HDS; Validation: AC, HDS, VS; Data recording: AC, AS; Formal analysis: AC, VS, AS, PS; Resources: HDS, AV; Writing & reviewing of manuscript: AC, HDS, AV, MG, PS; Supervision: HDS, AV, MG.

AVAILABILITY OF DATA

The datasets generated and analyzed for current study are presented in the main manuscript and as supplementary file. However, any additional information required can be taken from the corresponding author on reasonable request.

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COMPETING INTERESTS

The authors declare that they have no conflicts of interest or competing interests related to this research.

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922 **Table 1.** List of all the genotypes used in the experiment along with sources and acronyms used and experiment locations:

S. No.	Acronyms	Genotypes	Source
1	P1	Him Palam Mirch 2	CSK Himachal Pradesh Krishi Vishwavidyalaya, Palampur
2	P2	Him Palam Mirch 1	CSK Himachal Pradesh Krishi Vishwavidyalaya, Palampur
3	P3	Surajmukhi	CSK Himachal Pradesh Krishi Vishwavidyalaya, Palampur
4	P4	Pusa Jwala	Indian Agricultural Research Institute, New Delhi
5	P5	Punjab Guchhedar	Punjab Agricultural University, Ludhiana
6	P6	Pusa Sadabahar	Indian Agricultural Research Institute, New Delhi
7	P7 (check)	DKC-8 (check)	Dr YSPUHF, Nauni
Experimental Locations			
E1: Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, HP			
E2: Regional Horticulture Research and Training Station, Dhaula Kuan, Sirmour, HP			
E3: Regional Horticulture Research and Training Station, Bajaura, Kullu, HP			

923

924 **Table 2.** List of yield and other traits evaluation with method of assessment

Characteristics	Method of Assessment
Plant height (cm)	The height ten observational plants were measured from the ground level to the tip of the main stem
Number of fruits per plant	Total number of fruits from ten plants were counted at each picking then summed and averaged
Fruit weight (g)	The fruits were weighed in grams at harvestable maturity and average value was calculated.
Red ripe fruit yield per plant (g)	Total fruit weight of all red ripe fruits was taken at each picking and summed up for all the pickings and total weight was calculated.
Pedicle length (cm)	The lengths fruit pedicels were measured with the help of digital Vernier calliper
Number of seeds per fruit	Calculated by counting the seeds of ten oven dried red ripe fruits
Capsaicin content (%)	Capsaicin content in the samples was estimated by spectrophotometric measurement as per the procedure (Sadasivam 1992) under post-harvest fruit evaluation

925

926 **Table 3.** Analysis of variance (mean squares) over environments for different characters in chilli

Source of variation												
S.N.	Source of variation	Env. (E)	Rep/Env.	Genotypes (G)	Parents (P)	Hybrids (F1)	P vs F1	G × E	P × E	F1 × E	(P vs F1) × E	Pooled Error
1	Characters	2	6	27	6	20	1	54	12	40	2	162
2	Plant height	1500.99*	3.21	470.60*	364.30*	449.17*	1537.06*	40.71*	3.08	53.49*	10.96	4.15
3	Number of fruits per plant	3604.50*	4.15	9330.14*	3953.084 *	10788.680 *	12421.76*	179.58*	68.28*	218.99*	59.10*	15.40
4	Fruit weight (g)	1.70*	0.002	2.57*	2.40*	2.69*	1.20*	0.02*	0.03*	0.02*	0.004	0.01
5	Red ripe fruit yield per (g)	92799.20*	116.86	108779.50*	46562.23*	121345.80*	230757.40*	4095.79*	1995.07*	4906.74*	481.26*	98.42
6	Pedicle length (cm)	0.30*	0.01	1.78*	1.43*	1.95*	0.35*	0.008	0.002	0.01	0.01	0.01
7	Number of seeds per fruit	566.26*	19.77*	318.18*	348.17*	321.87*	64.49*	46.56*	2.40	59.58*	51.29*	8.03
8	Capsaicin (%)	0.008 *	0.001*	0.01*	0.02*	0.008 *	0.00	0.001 *	0.00	0.001 *	0.00	0.00

*Significant at $p \leq 0.05$ level of significance.

Table 4a. Mean performances of parents and hybrids across environments for plant height, number if fruits per plant, fruit weight and ripe fruit yield per plant

Genotypes	Plant height				Number of fruits per plant				Fruit weight				Ripe fruit yield per plant			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled
P1	68.1	67.87	59.17	65.05	126.33	115.67	111.47	117.82	3.76	3.5	3.37	3.54	473.72	405.28	375.29	418.1
P2	66.98	70.38	60.23	65.86	106	117	98.17	107.06	2.18	2.41	2.11	2.24	232.12	280.63	207.48	240.07
P3	63.24	66.42	57.31	62.33	107.67	122.33	99.19	109.73	2.19	2.49	2.26	2.31	217.23	299.54	243.97	253.58
P4	54.2	53.12	45.75	51.02	127.33	131.67	122.17	127.06	2.44	2.67	2.36	2.49	312.05	353.94	288.33	318.11
P5	71.89	75.57	65.13	70.86	127	141.33	122.3	130.21	2.51	2.75	2.43	2.56	321.13	382.94	298.01	334.02
P6	66.98	70.01	60.14	65.71	100.33	111.33	90.98	100.88	2.26	2.49	2.18	2.31	227.34	273.86	198.03	233.07
P7 (check)	69.22	72	63.21	68.14	66.67	74.33	61.86	67.62	3.21	3.48	3.1	3.26	216.35	252.77	191.56	220.23
P1× P2	78.36	81.3	71	76.89	138	149	132.43	139.81	3.74	4	3.61	3.78	518.33	594.05	478.05	530.15
P1× P3	73.62	72.15	64.2	69.99	121	128.33	116.16	121.83	2.98	3.24	2.89	3.04	362.57	410.43	336.48	369.82
P1× P4	62.92	62.1	54.23	59.75	103.67	105.67	97.48	102.27	2.62	2.85	2.55	2.67	272.42	308.73	248.57	276.57
P1× P5	77.84	76.9	68.32	74.35	174.67	158.33	139.19	157.4	4.02	3.76	3.63	3.8	699.96	596.07	505.88	600.63
P1× P6	93.46	79.56	61.34	78.12	149.67	112	83.45	115.04	4.11	4.37	3.98	4.16	619.96	462.52	331.99	471.49
P1× P7	83	81.75	73.8	79.52	187.67	182	172.24	180.63	2.92	2.7	2.63	2.75	551.04	492.32	452.42	498.59
P2 × P3	74.12	66.92	75.06	72.03	111.77	125	117	117.92	2.17	2.47	2.24	2.29	245.18	304.37	262.48	270.67
P2 × P4	61.87	64.59	56.25	60.9	111.67	114.67	105.1	110.48	2.47	2.68	2.39	2.51	275.47	311.96	251.55	279.66
P2 × P5	75.1	78.55	67.81	73.82	123.75	136.67	135.27	131.9	2.82	3.03	2.74	2.86	346.81	410.19	371.81	376.27
P2 × P6	67.35	70.37	62.1	66.61	100	106.33	94.09	100.14	2.76	2.99	2.69	2.81	277.42	315.1	253.11	281.88
P2 × P7	68.88	71.89	62.85	67.87	90	97.67	85.78	91.15	2.83	3.06	2.76	2.88	256.33	294.6	236.47	262.47
P3 × P4	63.8	66.73	58.15	62.89	92.33	99.33	85.89	92.52	2.23	2.44	2.16	2.28	202.48	242.29	182.65	209.14
P3 × P5	71.52	80.06	77.33	76.3	83	98.67	92	91.22	2.71	3.01	2.78	2.84	227.33	292.66	252.49	257.49
P3 × P6	68.62	77.17	74.18	73.32	67	72.33	61.76	67.03	2.13	2.42	2.18	2.24	167.57	221.95	188.52	192.68
P3 × P7	70.23	77.62	74.21	74.02	99.39	103.67	101.67	101.57	2.59	2.88	2.66	2.71	257.42	310.55	281.52	283.16
P4 × P5	63.65	62.14	55.82	60.54	219.67	221	210.07	216.91	2.13	2.35	2.07	2.19	475.76	511.43	435.53	474.24
P4 × P6	57.15	60.82	51.12	56.37	108.67	121	105.22	111.63	2.29	2.51	2.23	2.35	250.32	301.02	235.01	262.12
P4 × P7	64.18	67.08	58.48	63.25	128.67	136	123.14	129.27	2.53	2.76	2.46	2.59	327.45	377.25	303.34	336.01
P5 × P6	72.92	71.39	63.87	69.39	136	149	130	138.33	2.48	2.7	2.41	2.53	338.33	398.55	314.18	350.35
P5 × P7	81.78	85.16	75.15	80.7	136.5	143	130.11	136.54	3.45	3.68	3.33	3.49	471.86	523.54	433.26	476.22
P6 × P7	71.1	74.16	64.91	70.06	168	175	161.11	168.04	2.68	2.91	2.61	2.73	450.53	507.98	419.97	459.49
Mean	70.07	71.56	63.61	68.42	121.87	126.73	113.76	120.79	2.76	2.95	2.67	2.79	342.66	372.73	306.35	340.58
SE ±(m)	2.01	1.29	1.62		3.1	3.61	2.85		0.05	0.07	0.05		7.82	9.57	6.65	
CD (P≤0.05)	4.02	2.59	3.24		6.22	7.24	5.72		0.11	0.14	0.10		15.67	19.18	13.34	

E1: Dr. YSPUHF, Nauni E2: RHR&TS, Dhaula Kuan, E3: RHR&TS, Bajaura. *Genotypes acronyms given in Table.1.

Table 4b. Mean performances of parents and hybrids across environments for pedicel length, number of seeds per fruit and capsaicin (%)

Genotypes	Pedicel length				Number of seeds per fruit				Capsaicin (%)			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled
P1	3.40	3.40	3.33	3.38	53.73	52.27	50.33	52.11	0.21	0.21	0.20	0.21
P2	3.30	3.30	3.25	3.28	54.73	55.87	52.00	54.20	0.22	0.23	0.22	0.22
P3	3.00	3.07	3.01	3.03	50.67	52.00	50.00	50.89	0.23	0.24	0.22	0.23
P4	4.06	4.07	4.00	4.04	68.60	69.53	66.07	68.07	0.35	0.36	0.33	0.35
P5	4.03	4.03	3.99	4.02	56.27	57.27	54.73	56.09	0.32	0.32	0.31	0.32
P6	3.40	3.47	3.35	3.41	62.70	64.07	60.00	62.26	0.29	0.30	0.29	0.29
P7 (check)	3.23	3.23	3.10	3.19	53.27	56.53	50.53	53.44	0.26	0.26	0.25	0.26
P1× P2	3.11	3.13	2.98	3.07	59.73	62.87	57.93	60.18	0.19	0.23	0.20	0.21
P1× P3	3.20	3.30	3.00	3.17	55.53	57.67	52.33	55.18	0.22	0.23	0.21	0.22
P1× P4	3.20	3.17	3.10	3.15	57.33	62.00	54.27	57.87	0.32	0.30	0.25	0.29
P1× P5	2.77	2.77	2.75	2.76	61.60	60.00	56.47	59.36	0.27	0.28	0.26	0.27
P1× P6	4.02	4.07	4.00	4.03	81.27	70.80	63.53	71.87	0.25	0.27	0.24	0.25
P1× P7	3.09	3.13	2.98	3.07	54.00	58.47	50.13	54.20	0.24	0.25	0.24	0.24
P2 × P3	3.96	3.93	3.92	3.94	51.73	43.20	48.33	47.76	0.20	0.26	0.24	0.23
P2 × P4	3.22	3.30	3.18	3.23	54.93	60.33	53.07	56.11	0.23	0.26	0.24	0.24
P2 × P5	4.10	4.20	3.99	4.10	39.73	55.40	48.53	47.89	0.26	0.27	0.25	0.26
P2 × P6	4.32	4.43	4.00	4.25	53.93	62.27	59.13	58.44	0.28	0.29	0.26	0.28
P2 × P7	4.10	4.23	4.00	4.11	47.43	56.87	49.13	51.14	0.27	0.27	0.29	0.27
P3 × P4	3.00	3.07	2.96	3.01	54.33	58.87	50.13	54.44	0.27	0.29	0.26	0.27
P3 × P5	3.96	4.00	3.96	3.97	41.60	53.00	52.13	48.91	0.28	0.31	0.29	0.29
P3 × P6	3.35	3.40	3.33	3.36	40.00	54.93	46.93	47.29	0.27	0.27	0.25	0.26
P3 × P7	4.11	4.17	4.00	4.09	58.10	60.67	49.20	55.99	0.28	0.27	0.26	0.27
P4 × P5	3.30	3.33	3.10	3.24	59.87	55.97	55.73	57.19	0.34	0.29	0.32	0.32
P4 × P6	3.28	3.30	3.24	3.27	56.47	62.40	55.00	57.96	0.30	0.31	0.30	0.30
P4 × P7	3.51	3.53	3.48	3.51	58.20	59.33	57.13	58.22	0.32	0.35	0.28	0.32
P5 × P6	3.96	3.97	3.90	3.94	40.33	55.93	44.13	46.80	0.31	0.30	0.29	0.30
P5 × P7	3.51	3.57	3.47	3.51	55.80	64.00	67.93	62.58	0.31	0.32	0.29	0.31
P6 × P7	4.05	4.07	4.00	4.04	57.73	62.87	51.20	57.27	0.27	0.29	0.28	0.28
Mean	3.56	3.59	3.48	3.54	54.99	58.76	53.79	55.85	0.27	0.28	0.26	0.27
SE ±(m)	0.08	0.10	0.06		2.57	2.14	2.20		0.01	0.01	0.01	
CD (P≤0.05)	0.16	0.20	0.13		5.15	4.30	4.42		0.01	0.03	0.02	

E1: Dr. YSPUHF, Nauni E2: RHR&TS, Dhaula Kuan, E3: RHR&TS, Bajaura. ^aGenotypes acronyms given in Table.1.

Table 5a. GCA effects of parents for yield and quality traits across environments for plant height, number of fruits per plant, fruit weight and red ripe fruit yield per plant

Parents	Plant height				Number of fruits per plant				Fruit weight				Red ripe fruit yield per plant			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled
Him Palam Mirch 2	4.98*	1.89*	0.26	2.38*	16.93*	5.87*	5.98*	9.59*	0.65*	0.48*	0.52*	0.55*	136.72*	76.98*	72.57*	95.42*
Him Palam Mirch 1	-0.11	0.21	0.74*	0.28	-9.75*	-5.61*	-4.90*	-6.75*	-0.10*	-0.06*	-0.08*	-0.08*	-39.72*	-21.15*	-20.27*	-27.05*
Surajmukhi	-1.36*	0.11	3.21*	0.65*	-20.57*	-15.76*	-15.25*	-17.19*	-0.32*	-0.24*	-0.22*	-0.26*	-93.81*	-66.73*	-50.97*	-70.50*
Pusa Jwala	-8.74*	-9.20*	-9.26*	-9.07*	4.93*	5.24*	6.80*	5.66*	-0.32*	-0.29*	-0.31*	-0.31*	-34.81*	-24.59*	-24.17*	-27.86*
Punjab Guchhedar	2.89*	3.65*	3.30*	3.28*	16.96*	19.50*	19.02*	18.49*	0.06*	0.05*	0.05*	0.05*	51.23*	57.38*	50.93*	53.18*
Pusa Sadabahar	0.44	0.11	-1.23*	-0.22	-5.00*	-6.16*	-10.28*	-7.15*	-0.12*	-0.08*	-0.10*	-0.10*	-20.27*	-25.22*	-34.67*	-26.72*
DKC-8 (check)	1.89*	3.24*	2.99*	2.71*	-3.49*	-3.09*	-1.37*	-2.65*	0.15*	0.15*	0.14*	0.15*	0.67	3.33	6.59*	3.53*
SE. (gi) ±	0.44	0.28	0.35	0.21	0.68	0.79	0.62	0.4	0.01	0.02	0.01	0.007	1.71	2.09	1.45	1.02
SE. (gi-gj) ±	0.67	0.43	0.54	0.32	1.03	1.2	0.95	0.62	0.02	0.02	0.02	0.01	2.6	3.19	2.22	1.56

*Significant at $p \leq 0.05$ level of significance. E1=UHF, Nauni, E2=RHR&TS, DhaulaKuan and E3= RHR&TS, Bajaura.

Table 5b. GCA effects of parents for yield and quality traits across environments for pedicel length, number of seeds per fruit and capsaicin

Parents	Pedicel length				Number of seeds per fruit				Capsaicin			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled
Him Palam Mirch 2	-0.25*	-0.27*	-0.26*	-0.26*	4.12*	0.69	0.56	1.79*	-0.03*	-0.03*	-0.03*	-0.03*
Him Palam Mirch 1	0.11*	0.12*	0.08*	0.10*	-2.55*	-1.94*	-1.13*	-1.87*	-0.03*	-0.02*	-0.02*	-0.02*
Surajmukhi	-0.10*	-0.08*	-0.07*	-0.08*	-4.14*	-4.20*	-3.47*	-3.94*	-0.02*	-0.02*	-0.02*	-0.02*
Pusa Jwala	-0.09*	-0.10*	-0.08*	-0.09*	4.27*	3.10*	3.02*	3.46*	0.04*	0.03*	0.02*	0.03*
Punjab Guchhedar	0.14*	0.13*	0.15*	0.14*	-3.16*	-1.25*	0.46	-1.32*	0.03*	0.02*	0.03*	0.02*
Pusa Sadabahar	0.15*	0.16*	0.15*	0.15*	1.69*	3.03*	1.07*	1.93*	0.01*	0.01*	0.01*	0.01*
DKC-8 (check)	0.04*	0.05*	0.04*	0.04*	-0.23	0.57	-0.5	-0.05	0.01*	0.003	0.01*	0.01*
SE. (gi) ±	0.02	0.02	0.01	0.01	0.56	0.47	0.48	0.29	0.002	0.003	0.002	0.001
SE. (gi-gj) ±	0.03	0.03	0.02	0.02	0.86	0.71	0.73	0.45	0.002	0.004	0.003	0.002

*Significant at $p \leq 0.05$ level of significance. E1=UHF, Nauni, E2=RHR&TS, DhaulaKuan and E3= RHR&TS, Bajaura.

Table 6a. SCA effects of hybrids for yield and quality traits across environments for plant height, number of fruits per plant, fruit weight and ripe fruit yield per plant

Hybrids	Plant height				Number of fruits per plant				Fruit weight				Ripe fruit yield per plant			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled
P1× P2	3.41*	7.64 *	6.39 *	5.81 *	8.95*	22.01*	17.59*	16.18*	0.44*	0.63*	0.50*	0.52*	78.68*	165.49*	119.40*	121.19*
P1× P3	-0.08	-1.41	-2.88 *	-1.45 *	2.77	11.49*	11.67*	8.64*	-0.11 *	0.05	-0.08*	-0.05*	-23.00*	27.44*	8.53	4.32
P1× P4	-3.39*	-2.15 *	-0.39	-1.98 *	-40.06 *	-32.18*	-29.06*	-33.77*	-0.47*	-0.28*	-0.33*	-0.36*	-172.15*	-116.39*	-106.19*	-131.58*
P1× P5	-0.1	-0.2	1.15	0.28	18.91*	6.23*	0.44	8.56*	0.55*	0.28*	0.39*	0.41*	169.36*	88.97*	76.03*	111.45*
P1× P6	17.96*	6.00 *	-1.3	7.56*	15.86*	-14.44*	-26.01*	-8.19*	0.83*	1.03*	0.90*	0.92*	160.86*	38.03*	-12.27*	62.21*
P1× P7	6.06*	5.06 *	6.94 *	6.02 *	52.36*	52.49*	53.87*	52.91*	-0.64*	-0.88*	-0.70*	-0.74*	70.99*	39.28*	66.91 *	59.06*
P2 × P3	5.51*	-4.96 *	7.50 *	2.68 *	20.23*	19.64*	23.39*	21.08*	-0.17*	-0.18*	-0.14*	-0.16*	36.05*	19.51*	27.36*	27.64*
P2 × P4	0.64	2.02 *	1.16	1.27 *	-5.38*	-11.69*	-10.56*	-9.21*	0.13*	0.09	0.11*	0.11*	7.34	-15.04*	-10.37*	-6.02*
P2 × P5	2.24	3.13 *	0.17	1.85 *	-5.32*	-3.95	7.39*	-0.63	0.10*	0.10*	0.10*	0.10*	-7.35	1.22	34.80*	9.56*
P2 × P6	-3.06*	-1.51	-1.02	-1.86 *	-7.12*	-8.62*	-4.49*	-6.75*	0.23*	0.18*	0.20*	0.20*	-5.25	-11.26	1.69	-4.94
P2 × P7	-2.98*	-3.12 *	-4.49 *	-3.53 *	-18.63*	-20.36*	-21.71*	-20.23*	0.02	0.02	0.02	0.02	-47.28*	-60.31*	-56.20*	-54.60*
P3 × P4	3.82*	4.26 *	0.59	2.89 *	-13.90*	-16.89*	-19.42*	-16.73*	0.11*	0.03	0.01	0.05*	-11.57*	-39.13*	-48.56*	-33.09*
P3 × P5	-0.09	4.74 *	7.22 *	3.96 *	-35.26*	-31.81*	-25.53*	-30.86*	0.21*	0.26*	0.28*	0.25*	-72.75*	-70.73*	-53.82*	-65.77*
P3 × P6	-0.54	5.39 *	8.59 *	4.48 *	-29.30*	-32.47*	-26.48*	-29.42*	-0.19*	-0.21 *	-0.17*	-0.19*	-61.01*	-58.83*	-32.20*	-50.68*
P3 × P7	-0.38	2.71 *	4.40 *	2.24 *	1.58	-4.21	4.52*	0.63	0.001	0.02	0.07*	0.03	7.9	1.22	19.55*	9.56*
P4 × P5	-0.57	-3.87 *	-1.83	-2.09 *	75.91*	69.53*	70.49*	71.98*	-0.36*	-0.35*	-0.34*	-0.35*	116.68*	105.90*	102.42*	108.34*
P4 × P6	-4.63*	-1.65	-2	-2.76 *	-13.14*	-4.81*	-5.06*	-7.67*	-0.02	-0.06	-0.03	-0.04	-37.25*	-21.90*	-12.51*	-23.89*
P4 × P7	0.95	1.48	1.14	1.19	5.36*	7.12*	3.95*	5.48*	-0.05	-0.04	-0.04	-0.04*	18.93*	25.78*	14.57*	19.76*
P5 × P6	-0.49	-3.93 *	-1.81	-2.07 *	2.17	8.94*	7.50*	6.20*	-0.22*	-0.22*	-0.21*	-0.22*	-35.28*	-6.34	-8.44	-16.69*
P5 × P7	6.93*	6.71 *	5.25 *	6.30 *	1.16	-0.14	-1.3	-0.09	0.47*	0.53*	0.47*	0.49*	77.31*	90.10*	69.40*	78.93*
P6 × P7	-1.31	-0.75	-0.46	-0.84	54.62*	57.53*	59.00*	57.05*	-0.11*	-0.11 *	-0.11 *	-0.11*	127.47*	157.15*	141.70*	142.11*
SE (S_{ij})	2.66	1.71	2.14	0.52	4.11	4.78	3.78	1	0.07	0.09	0.06	0.02	10.35	12.67	8.81	2.53
SE (S_{ij}-S_{ik})	3.95	2.54	3.18	1.79	6.1	7.1	5.61	3.44	0.11	0.14	0.1	0.06	15.37	18.82	13.08	8.71
SE (S_{ij}-S_{kl})	3.69	2.38	2.97	1.67	5.71	6.64	5.25	3.22	0.1	0.13	0.09	0.06	14.38	17.6	12.24	8.14
Crosses in significant direction	6	10	7	11	8	10	10	9	9	7	10	9	9	10	10	11

*Significant at $p \leq 0.05$ level of significance. E1=UHF, Nauni, E2=RHR&TS, DhaulaKuan and E3= RHR&TS, Bajaura. ^aHybrids acronyms given in Table. 1.

Table 6b. SCA effects of hybrids for yield and quality traits across environments for plant height, number of fruits per plant, fruit weight and ripe fruit yield per plant

Hybrids	Pedicel length				Number of seeds per fruit				Capsaicin			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled
P1× P2	-0.30*	-0.32*	-0.32*	-0.31*	3.18	5.35*	4.72*	4.42*	-0.02*	0.002	-0.01	-0.01*
P1× P3	-0.01	0.05	-0.15*	-0.03	0.57	2.41	1.46	1.48	-0.003	-0.01	-0.004	-0.004
P1× P4	-0.02	-0.06	-0.04	-0.04	-6.04*	-0.55	-3.10*	-3.23*	0.04*	0.02	-0.004	0.02*
P1× P5	-0.67*	-0.69*	-0.62*	-0.66*	5.66*	1.8	1.67	3.04*	0	0.01	0.01	0.01
P1× P6	0.57*	0.58*	0.63*	0.59*	20.47*	8.32*	8.12*	12.30*	-0.003	0.01	-0.01	0.00
P1× P7	-0.26*	-0.24*	-0.27*	-0.26*	-4.87*	-1.56	-3.71*	-3.38*	-0.008	-0.003	0.01	0.00
P2 × P3	0.39*	0.30*	0.43*	0.38*	3.43*	-9.43*	-0.85	-2.28*	-0.02*	0.02	0.01*	0.01
P2 × P4	-0.36*	-0.31*	-0.30*	-0.32*	-1.78	0.41	-2.61	-1.33	-0.04*	-0.03*	-0.02*	-0.03*
P2 × P5	0.30*	0.36*	0.28*	0.31*	-9.55*	-0.17	-4.58*	-4.77*	-0.006	-0.01	-0.02*	-0.01*
P2 × P6	0.51*	0.56*	0.29*	0.45*	-0.20	2.42	5.41*	2.54*	0.03*	0.02*	0.01	0.02*
P2 × P7	0.39*	0.47*	0.41*	0.42*	-4.77*	-0.53	-3.02*	-2.78*	0.03*	0.01	0.04*	0.02*
P3 × P4	-0.37*	-0.34*	-0.36*	-0.36*	-0.78	1.21	-3.20*	-0.93	-0.02*	-0.004	-0.01	-0.01*
P3 × P5	0.37*	0.36*	0.41*	0.38*	-6.09*	-0.31	1.36	-1.68*	0.002	0.02*	0.02*	0.01*
P3 × P6	-0.26*	-0.27*	-0.23*	-0.25*	-12.54*	-2.66	-4.45*	-6.55*	0.01	-0.01	-0.01	-0.002
P3 × P7	0.61*	0.61*	0.56*	0.59*	7.49*	5.53*	-0.62	4.13*	0.02*	-0.003	0.01	0.01*
P4 × P5	-0.30*	-0.29*	-0.44*	-0.34*	3.77*	-4.64*	-1.53	-0.8	0.01	-0.04*	0.01	-0.01*
P4 × P6	-0.33*	-0.35*	-0.31*	-0.33*	-4.48*	-2.48	-2.88	-3.28*	-0.02*	-0.01	0.003	-0.01*
P4 × P7	0.004	-0.005	0.05	0.02	-0.83	-3.10*	0.83	-1.03	0.01	0.03*	-0.01	0.01*
P5 × P6	0.12*	0.09	0.13*	0.11*	-13.19*	-4.60*	-11.18*	-9.66*	0.001	-0.01	-0.01	-0.01
P5 × P7	-0.23*	-0.20*	-0.19*	-0.21*	4.21*	5.92*	14.19*	8.10*	0.007	0.02*	-0.002	0.01*
P6 × P7	0.30*	0.27*	0.34*	0.30*	1.29	0.51	-3.16*	-0.46	-0.02*	-0.002	0.001	-0.01
SE (S_{ij})	0.11	0.13	0.08	0.03	3.40	2.84	2.92	0.72	0.01	0.02	0.01	0.003
SE (S_{ij}-S_{ik})	0.16	0.20	0.12	0.09	5.05	4.22	4.33	2.49	0.01	0.03	0.02	0.01
SE (S_{ij}-S_{kl})	0.15	0.18	0.12	0.08	4.73	3.94	4.05	2.33	0.01	0.02	0.02	0.01
Crosses in significant direction	9	9	10	9	6	4	4	6	4	4	3	7

*Significant at $p \leq 0.05$ level of significance. E1=UHF, Nauni, E2=RHR&TS, DhaulaKuan and E3= RHR&TS, Bajaura. *Hybrids acronyms given in Table. 1.

Table 7a. Heterosis over better parent and standard check for plant height and number of fruits per plant

Genotype	Plant height								Number of fruits per plant							
	(BP %)				(SH %)				(BP %)				(SH %)			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled
P1×P2	15.07 *	15.51 *	17.88 *	16.73 *	13.20 *	12.91 *	12.32 *	12.83 *	9.23 *	27.35 *	18.80 *	18.66 *	107.00 *	100.45 *	114.07 *	106.76 *
P1×P3	8.11 *	6.31 *	8.51 *	7.60 *	6.36 *	0.21	1.57	2.71	-4.22	4.9	4.21	3.4	81.50 *	72.65 *	87.78 *	80.17 *
P1×P4	-7.60 *	-8.50 *	-8.35 *	-8.14 *	-9.10 *	-13.75 *	-14.21 *	-12.32 *	-18.59 *	-19.75 *	-20.21 *	-19.51 *	55.50 *	42.15 *	57.58 *	51.24 *
P1×P5	8.27 *	1.77	4.9	4.93 *	12.45 *	6.81 *	8.08 *	9.11 *	37.53 *	12.03 *	13.81 *	20.88 *	162.00 *	113.00 *	125.01 *	132.77 *
P1×P6	37.24 *	13.65 *	2	18.89 *	35.01 *	10.50 *	-2.95	14.64 *	18.47 *	-3.17	-25.14 *	-2.36	124.50 *	50.67 *	34.90 *	70.13 *
P1×P7	19.91 *	13.54 *	16.75 *	16.69 *	19.91 *	13.54 *	16.75 *	16.69 *	48.55 *	57.35 *	54.51 *	53.31 *	181.50 *	144.84 *	178.43 *	167.13 *
P2×P3	10.66 *	-4.92 *	24.62 *	9.36 *	7.08 *	-7.06 *	18.74 *	5.71 *	3.81	2.18	17.96 *	7.47 *	67.66 *	68.16 *	89.14 *	74.39 *
P2×P4	-7.63 *	-8.23 *	-6.61 *	-7.53 *	-10.62 *	-10.29 *	-11.01 *	-10.62 *	-12.30 *	-12.91 *	-13.97 *	-13.05 *	67.50 *	54.26 *	69.91 *	63.38 *
P2×P5	4.47	3.95 *	4.11	4.17	8.49 *	9.10 *	7.28 *	8.33 *	-2.56	-3.3	10.60 *	1.29	85.63 *	83.86 *	118.67 *	95.05 *
P2×P6	0.56	-0.02	3.1	1.13	-2.7	-2.27	-1.76	-2.26	-5.66	-9.12 *	-4.16	-6.46 *	50.00 *	43.05 *	52.11 *	48.10 *
P2×P7	-0.49	-0.15	-0.57	-0.39	-0.49	-0.15	-0.57	-0.39	-15.09 *	-16.52 *	-12.62 *	-14.86 *	35.00 *	31.39 *	38.67 *	34.80 *
P3×P4	0.88	0.47	1.46	0.91	-7.83 *	-7.31 *	-8.01 *	-7.70 *	-27.49 *	-24.56 *	-29.70 *	-27.18 *	38.50 *	33.63 *	38.84 *	36.82 *
P3×P5	-0.52	5.95 *	18.73 *	7.68 *	3.32	11.19 *	22.34 *	11.97 *	-34.65 *	-30.19 *	-24.78 *	-29.94 *	24.50 *	32.74 *	48.72 *	34.90 *
P3×P6	2.45	10.23 *	23.35 *	11.59 *	-0.87	7.18 *	17.35 *	7.60 *	-37.77 *	-40.87 *	-37.74 *	-38.91 *	0.5	-2.69	-0.17	-0.87
P3×P7	1.46	7.80 *	17.40 *	8.62 *	1.46	7.80 *	17.40 *	8.62 *	-7.69 *	-15.26 *	2.5	-7.43 *	49.08 *	39.46 *	64.35 *	50.21 *
P4×P5	-11.46 *	-17.77 *	-14.29 *	-14.57 *	-8.04 *	-13.69 *	-11.69 *	-11.16 *	72.51 *	56.37 *	71.76 *	66.58 *	229.50 *	197.31 *	239.58 *	220.78 *
P4×P6	-14.68 *	-13.12 *	-14.99 *	-14.22 *	-17.44 *	-15.52 *	-19.12 *	-17.28 *	-14.66 *	-8.10 *	-13.87 *	-12.14 *	63.00 *	62.78 *	70.10 *	65.08 *
P4×P7	-7.28 *	-6.84 *	-7.48 *	-7.19 *	-7.28 *	-6.84 *	-7.48 *	-7.19 *	1.05	3.29	0.79	1.74	93.00 *	82.96 *	99.06 *	91.17 *
P5×P6	1.43	-5.53 *	-1.93	-2.07	5.34	-0.85	1.04	1.83	7.09 *	5.42 *	6.30 *	6.24 *	104.00 *	100.45 *	110.15 *	104.57 *
P5×P7	13.76 *	12.70 *	15.38 *	13.88 *	18.15 *	18.28 *	18.89 *	18.42 *	7.48 *	1.18	6.39 *	4.86	104.75 *	92.38 *	110.34 *	101.92 *
P6×P7	2.72	3	2.69	2.81	2.72	3	2.69	2.81	67.44 *	57.19 *	77.09 *	66.57 *	152.00 *	135.43 *	160.45 *	148.50 *
SE±	2.59	2.9	1.14	1.22	2.59	2.9	1.14	1.22	4.03	5.7	2.02	2.5	4.03	5.7	2.02	2.5

*Significant at $p \leq 0.05$ level of significance. E1=UHF, Nauni, E2=RHR&TS, DhaulaKuan and E3= RHR&TS, Bajaura; BP: Better parent; SH: Standard heterosis ^aHybrids acronyms given in Table 1.

Table 7b. Heterosis over better parent and standard check for fruit weight and ripe fruit yield per plant

Genotype	Fruit weight								Ripe fruit yield per plant							
	(BP %)				(SH %)				(BP %)				(SH %)			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled
P1× P2	-0.44	14.39 *	7.23 *	6.87 *	16.39 *	15.05 *	16.58 *	15.97 *	9.42 *	46.58 *	27.38 *	26.80 *	139.58 *	135.01 *	149.56 *	140.73 *
P1× P3	-20.76 *	-7.44 *	-14.06 *	-14.25 *	-7.37 *	-6.90 *	-6.57 *	-6.95 *	-23.46 *	1.27	-10.34 *	-11.55 *	67.59 *	62.37 *	75.65 *	67.93 *
P1× P4	-30.35 *	-18.49 *	-24.26 *	-24.51 *	-18.57 *	-18.02 *	-17.65 *	-18.09 *	-42.49 *	-23.82 *	-33.77 *	-33.85 *	25.92 *	22.14 *	29.76 *	25.59 *
P1× P5	6.92 *	7.44 *	7.72 *	7.34 *	25.00 *	8.05 *	17.12 *	16.49 *	47.76 *	47.07 *	34.80 *	43.66 *	223.53 *	135.81 *	164.08 *	172.73 *
P1× P6	9.49 *	25.07 *	18.32 *	17.42 *	28.01 *	25.79 *	28.63 *	27.42 *	30.87 *	14.12 *	-11.54 *	12.77 *	186.56 *	82.98 *	73.31 *	114.09 *
P1× P7	-22.36 *	-22.88 *	-21.88 *	-22.38 *	-9.23 *	-22.44 *	-15.07 *	-15.77 *	16.32 *	21.47 *	20.55 *	19.25 *	154.70 *	94.77 *	136.17 *	126.40 *
P2 × P3	-1.07	-0.94	-1.03	-1.01	-32.57 *	-29.05 *	-27.77 *	-29.80 *	5.63	1.61	7.58 *	6.74 *	13.33 *	20.41 *	37.02 *	22.91 *
P2 × P4	1.23	0.5	1.41	1.03	-23.24 *	-22.82 *	-22.71 *	-22.92 *	-11.72 *	-11.86 *	-12.76 *	-12.09 *	27.33 *	23.41 *	31.32 *	26.99 *
P2 × P5	12.07 *	10.44 *	12.74 *	11.70 *	-12.34 *	-12.75 *	-11.41 *	-12.19 *	8.00 *	7.12 *	24.77 *	12.65 *	60.30 *	62.27 *	94.10 *	70.86 *
P2 × P6	22.30 *	20.24 *	23.39 *	21.91 *	-14.11 *	-14.00 *	-13.13 *	-13.76 *	19.52 *	12.29 *	21.99 *	17.41 *	28.23 *	24.66 *	32.13 *	27.99 *
P2 × P7	-12.03 *	-12.08 *	-10.98 *	-11.72 *	-12.03 *	-12.08 *	-10.98 *	-11.72 *	10.43 *	4.98	13.98 *	9.33 *	18.48 *	16.55 *	23.45 *	19.18 *
P3 × P4	-8.62 *	-8.49 *	-8.47 *	-8.53 *	-30.71 *	-29.72 *	-30.25 *	-30.21 *	-35.11 *	-31.54 *	-36.65 *	-34.26 *	-6.41	-4.15	-4.65	-5.04
P3 × P5	7.96 *	9.71 *	14.38 *	10.62 *	-15.56 *	-13.33 *	-10.12 *	-13.04 *	-29.21 *	-23.57 *	-15.27 *	-22.91 *	5.08	15.78 *	31.81 *	16.92 *
P3 × P6	-5.76 *	-2.95	-3.39	-3.07	-33.82 *	-30.49 *	-29.49 *	-31.27 *	-26.29 *	-25.90 *	-22.73 *	-24.02 *	-22.55 *	-12.19 *	-1.59	-12.51 *
P3 × P7	-19.40 *	-17.16 *	-13.99 *	-16.89 *	-19.40 *	-17.16 *	-13.99 *	-16.89 *	18.50 *	3.68	15.39 *	11.67 *	18.98 *	22.86 *	46.96 *	28.58 *
P4 × P5	-15.12 *	-14.32 *	-14.79 *	-14.73 *	-33.61 *	-32.31 *	-33.05 *	-32.97 *	48.15 *	33.55 *	46.15 *	41.98 *	119.90 *	102.33 *	127.36 *	115.34 *
P4 × P6	-5.88 *	-5.87 *	-5.37 *	-5.71 *	-28.63 *	-27.71 *	-27.88 *	-28.07 *	-19.78 *	-14.95 *	-18.49 *	-17.60 *	15.70 *	19.09 *	22.68 *	19.02 *
P4 × P7	-21.16 *	-20.52 *	-20.45 *	-20.71 *	-21.16 *	-20.52 *	-20.45 *	-20.71 *	4.93	6.59 *	5.20 *	5.63 *	51.35 *	49.24 *	58.35 *	52.58 *
P5 × P6	-1.46	-1.82	-0.82	-1.39	-22.93 *	-22.44 *	-22.07 *	-22.48 *	5.36 *	4.08	5.43 *	4.89 *	56.38 *	57.67 *	64.01 *	59.09 *
P5 × P7	7.26 *	5.85 *	7.53 *	6.85 *	7.26 *	5.85 *	7.53 *	6.85 *	46.94 *	36.72 *	45.39 *	42.57 *	118.11 *	107.12 *	126.18 *	116.24 *
P6 × P7	-16.70 *	-16.40 *	-15.82 *	-16.31 *	-16.70 *	-16.40 *	-15.82 *	-16.31 *	98.18 *	85.49 *	112.08 *	97.14 *	108.24 *	100.96 *	119.24 *	108.65 *
SE±	0.12	0.13	0.03	0.03	0.12	0.13	0.03	0.03	17.93	16.19	4.7	11.04	17.93	16.19	4.7	11.04

*Significant at $p \leq 0.05$ level of significance. E1=UHF, Nauni, E2=RHR&TS, DhaulaKuan and E3= RHR&TS, Bajaura; BP: Better parent; SH: Standard heterosis ^aHybrids acronyms given in Table 1.

Table 7c. Heterosis over better parent and standard check for pedicel length and number of seeds per fruit

Genotype	Pedicel length								Number of seeds per fruit							
	(BP %)				(SH %)				(BP %)				(SH %)			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled	E1	E2	E3	Pooled
P1× P2	-8.62 *	-7.84 *	-10.60 *	-9.01 *	-3.81	-3.09	-3.87	-3.59	9.14	12.53 *	11.41 *	11.03 *	12.14 *	11.20 *	14.64 *	12.60 *
P1× P3	-5.97 *	-2.94	-10.00 *	-6.28 *	-1.03	2.06	-3.23	-0.7	3.35	10.33 *	3.97	5.88	4.26	2	3.56	3.24
P1× P4	-21.18 *	-22.13 *	-22.65 *	-21.98 *	-1.03	-2.06	-0.11	-1.08	-16.42 *	-10.83 *	-17.86 *	-14.99 *	7.63	9.67 *	7.39	8.27
P1× P5	-31.32 *	-31.40 *	-31.08 *	-31.27 *	-14.33 *	-14.43 *	-11.29 *	-13.38 *	9.48	4.77	3.17	5.82	15.64 *	6.13	11.74 *	11.06 *
P1× P6	18.12 *	17.31 *	19.52 *	18.30 *	24.33 *	25.77 *	29.03 *	26.34 *	29.61 *	10.51 *	5.89	15.44 *	52.57 *	25.24 *	25.73 *	34.47 *
P1× P7	-9.21 *	-7.84 *	-10.50 *	-9.17 *	-4.43	-3.09	-3.76	-3.76	0.5	3.42	-0.79	1.41	1.38	3.42	-0.79	1.41
P2 × P3	20.00 *	19.19 *	20.51 *	19.90 *	22.47 *	21.65 *	26.34 *	23.45 *	-5.48	-22.67 *	-7.05	-11.89 *	-2.88	-23.58 *	-4.35	-10.64 *
P2 × P4	-20.77 *	-18.85 *	-20.65 *	-20.09 *	-0.52	2.06	2.47	1.32	-19.92 *	-13.23 *	-19.68 *	-17.56 *	3.13	6.72	5.01	4.99
P2 × P5	1.65	4.13	0	1.94	26.80 *	29.90 *	28.71 *	28.47 *	-29.38 *	-3.26	-11.33 *	-14.62 *	-25.41 *	-2	-3.96	-10.40 *
P2 × P6	26.93 *	27.88 *	19.42 *	24.80 *	33.61 *	37.11 *	28.92 *	33.28 *	-13.98 *	-2.81	-1.44	-6.12	1.25	10.14 *	17.02 *	9.36 *
P2 × P7	24.24 *	28.28 *	23.08 *	25.21 *	26.80 *	30.93 *	29.03 *	28.92 *	-13.34 *	0.59	-5.51	-5.64	-10.95 *	0.59	-2.77	-4.3
P3 × P4	-26.19 *	-24.59 *	-26.06 *	-25.61 *	-7.32 *	-5.15	-4.52 *	-5.68 *	-20.80 *	-15.34 *	-24.12 *	-20.01 *	2	4.13	-0.79	1.87
P3 × P5	-1.82	-0.83	-0.75	-1.13	22.47 *	23.71 *	27.74 *	24.60 *	-26.07 *	-7.45	-4.75	-12.80 *	-21.90 *	-6.25	3.17	-8.48
P3 × P6	-1.57	-1.92	-0.5	-1.34	3.61	5.15	7.42 *	5.37 *	-36.20 *	-14.26 *	-21.78 *	-24.04 *	-24.91 *	-2.83	-7.12	-11.52 *
P3 × P7	27.11 *	28.87 *	29.03 *	28.33 *	27.11 *	28.87 *	29.03 *	28.33 *	9.07	7.31	-2.64	4.76	9.07	7.31	-2.64	4.76
P4 × P5	-18.72 *	-18.03 *	-22.56 *	-19.76 *	2.06	3.09	0	1.74	-12.73 *	-19.51 *	-15.64 *	-15.98 *	12.39 *	-1	10.29 *	7.01
P4 × P6	-19.21 *	-18.85 *	-19.15 *	-19.07 *	1.44	2.06	4.41 *	2.61	-17.69 *	-10.26 *	-16.75 *	-14.85 *	6.01	10.38 *	8.84	8.44
P4 × P7	-13.46 *	-13.11 *	-13.07 *	-13.22 *	8.66 *	9.28 *	12.26 *	10.03 *	-15.16 *	-14.67 *	-13.52 *	-14.46 *	9.26	4.95	13.06 *	8.94 *
P5 × P6	-1.9	-1.65	-2.26	-1.94	22.37 *	22.68 *	25.81 *	23.59 *	-35.67 *	-12.70 *	-26.44 *	-24.83 *	-24.28 *	-1.06	-12.66 *	-12.43 *
P5 × P7	-13.06 *	-11.57 *	-13.03 *	-12.55 *	8.45 *	10.31 *	11.94 *	10.21 *	-0.83	11.76 *	24.12 *	11.57 *	4.76	13.21 *	34.43 *	17.09 *
P6 × P7	19.10 *	17.31 *	19.52 *	18.63 *	25.36 *	25.77 *	29.03 *	26.69 *	-7.92	-1.87	-14.67 *	-8.01 *	8.39	11.20 *	1.32	7.15
SE±	0.16	0.15	0.04	0.03	0.16	0.15	0.04	0.03	2.12	2.29	1.56	1.4	2.12	2.29	1.56	1.4

*Significant at $p \leq 0.05$ level of significance. E1=UHF, Nauni, E2=RHR&TS, DhaulaKuan and E3= RHR&TS, Bajaura; BP: Better parent; SH: Standard heterosis ^aHybrids acronyms given in Table 1.

Table 7d. Heterosis over better parent and standard check for capsaicin

Genotype	Capsaicin							
	(BP %)				(SH %)			
	E1	E2	E3	Pooled	E1	E2	E3	Pooled
P1× P2	-15.15 *	0	-9.09 *	-7.92	-28.21 *	-11.39 *	-21.05 *	-20.17 *
P1× P3	-4.35	-4.11	-4.55	-4.33	-15.38 *	-11.39 *	-17.11 *	-14.59 *
P1× P4	-9.52 *	-17.43 *	-24.24 *	-16.93 *	21.79 *	13.92 *	-1.32	11.59 *
P1× P5	-15.62 *	-12.37 *	-15.22 *	-14.39 *	3.85	7.59	2.63	4.72
P1× P6	-13.79 *	-9.89 *	-18.39 *	-13.96 *	-3.85	3.8	-6.58	-2.15
P1× P7	-7.69 *	-3.8	-5.26	-5.58	-7.69 *	-3.8	-5.26	-5.58
P2 × P3	-11.59 *	6.85	9.09 *	1.44	-21.79 *	-1.27	-5.26	-9.44 *
P2 × P4	-34.29 *	-29.36 *	-26.26 *	-30.03 *	-11.54 *	-2.53	-3.95	-6.01
P2 × P5	-18.75 *	-15.46 *	-18.48 *	-17.54 *	0	3.8	-1.32	0.86
P2 × P6	-3.45	-3.3	-10.34 *	-5.66	7.69 *	11.39 *	2.63	7.3
P2 × P7	3.85	1.27	13.16 *	6.01	3.85	1.27	13.16 *	6.01
P3 × P4	-22.86 *	-19.27 *	-21.21 *	-21.09 *	3.85	11.39 *	2.63	6.01
P3 × P5	-12.50 *	-5.15	-4.35	-7.37 *	7.69 *	16.46 *	15.79 *	13.30 *
P3 × P6	-6.90 *	-10.99 *	-13.79 *	-10.57 *	3.85	2.53	-1.32	1.72
P3 × P7	7.69 *	1.27	1.32	3.43	7.69 *	1.27	1.32	3.43
P4 × P5	-2.86	-19.27 *	-4.04	-8.95 *	30.77 *	11.39 *	25.00 *	22.32 *
P4 × P6	-14.29 *	-14.68 *	-9.09 *	-12.78 *	15.38 *	17.72 *	18.42 *	17.17 *
P4 × P7	-8.57 *	-4.59	-15.15 *	-9.27 *	23.08 *	31.65 *	10.53 *	21.89 *
P5 × P6	-3.12	-6.19	-5.43	-4.91	19.23 *	15.19 *	14.47 *	16.31 *
P5 × P7	-3.12	0	-5.43	-2.81	19.23 *	22.78 *	14.47 *	18.88 *
P6 × P7	-6.90 *	-3.3	-3.45	-4.53	3.85	11.39 *	10.53 *	8.58 *
SE±	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*Significant at $p \leq 0.05$ level of significance. E1=UHF, Nauni, E2=RHR&TS, DhauraKuan and E3= RHR&TS, Bajaura; BP: Better parent; SH: Standard heterosis

^aHybrids acronyms given in Table 1.

Table 8. Pearson's correlation coefficient analysis relationship of combining ability, standard heterosis and F_1 's for yield and quality traits

Traits	GCA-SCA	GCA-F1	GCA-EH	SCA-F1	SCA-EH	F1-EH
Fruit yield per plant	0.4	0.84	0.84	0.84*	0.84*	1.00*
Plant height	0.32	0.88	0.88	0.73*	0.73*	1.00*
Number of fruits per plant	0.24	0.62	0.62	0.91*	0.91*	1.00*
Fruit weight	0.18	0.77	0.77	0.77*	0.77*	1.00*
Pedicle length	0.32	0.64	0.65	0.93*	0.93*	1.00*
Number of seeds per fruit	0.06	0.57	0.57	0.85*	0.85*	1.00*
Capsaicin	-0.19	0.89	0.9	0.23	0.22	1.00*

*Significant at $p \leq 0.05$ level of significance

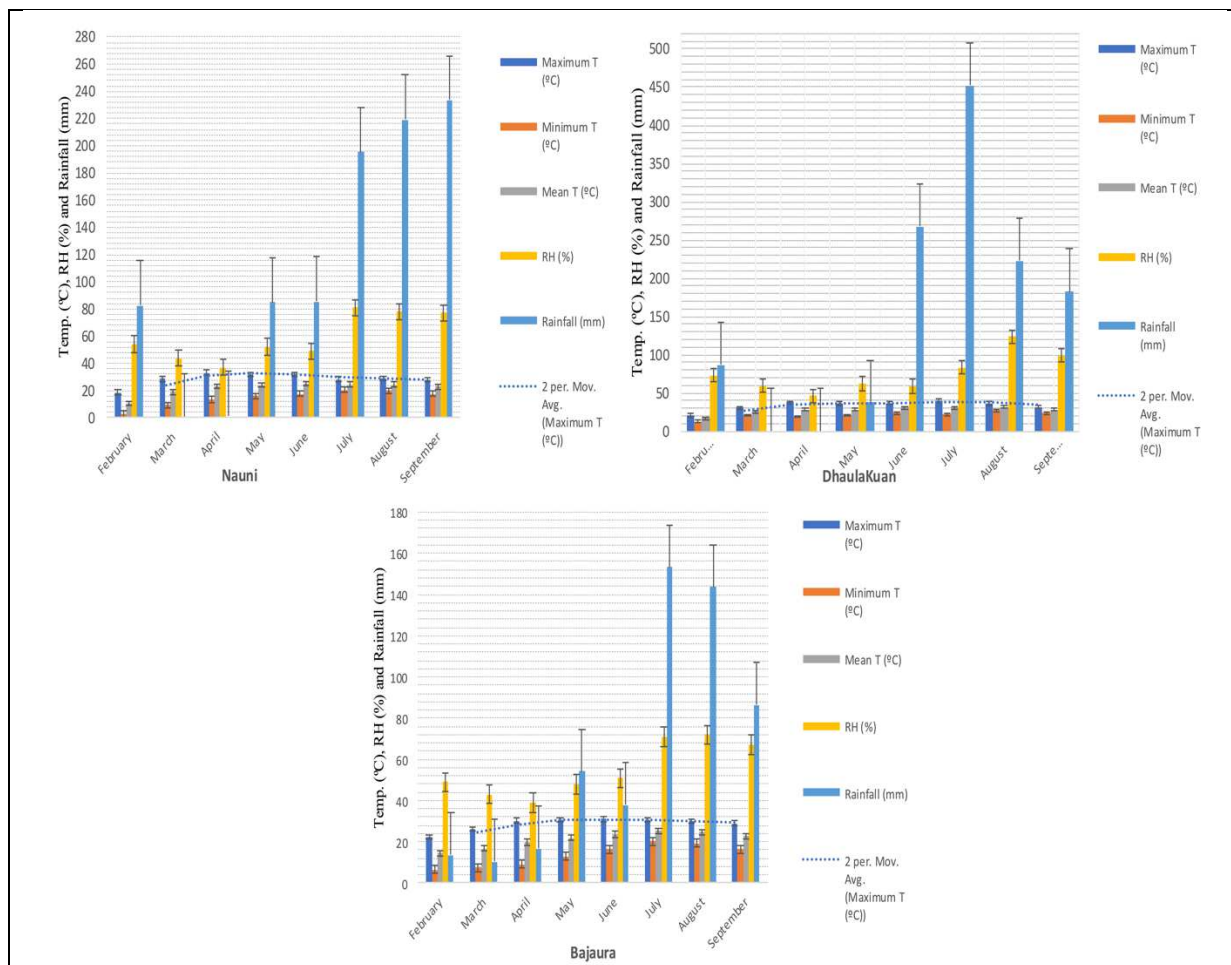


Fig. 1 Monthly Temp ($^{\circ}\text{C}$), RH (%) and Rainfall (mm) at (i). Nauni (ii). RHR&TS, Dhaula Kuan (iii). RHR&TS, Bajaura, HP

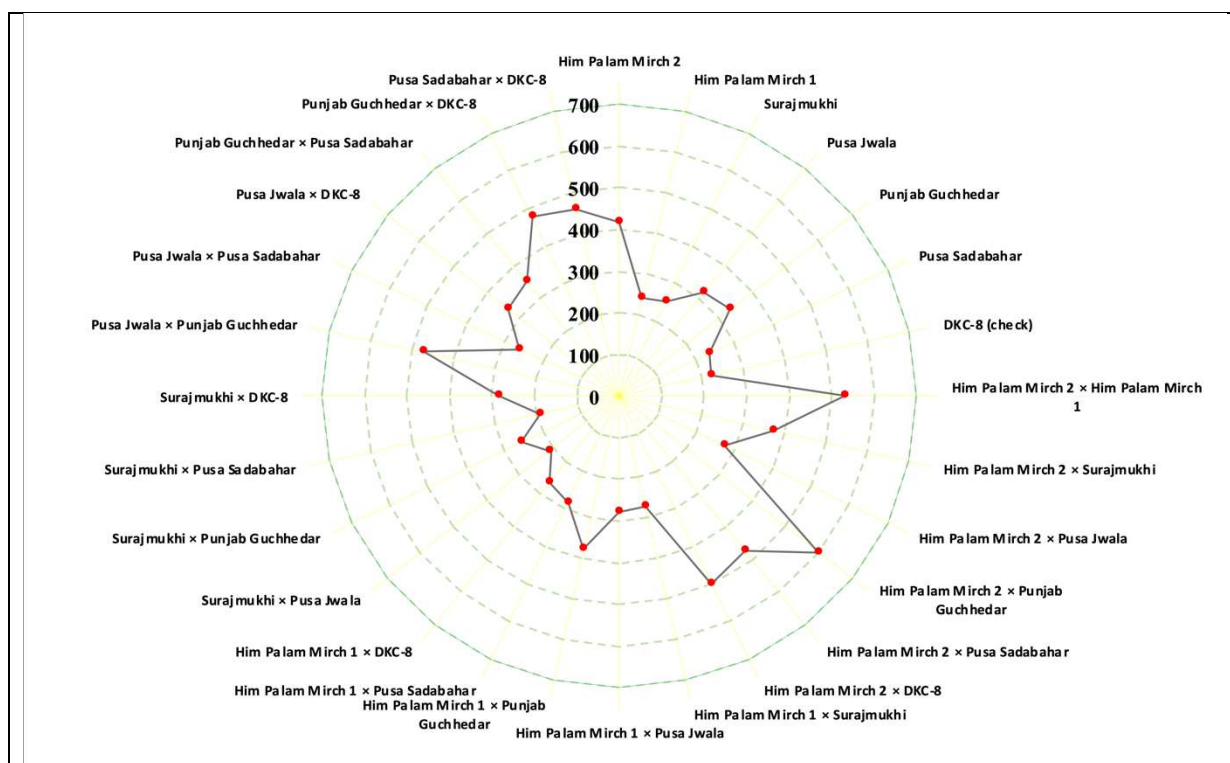


Fig. 2 Per se performance of Parents and 21 F₁'s at pooled environments

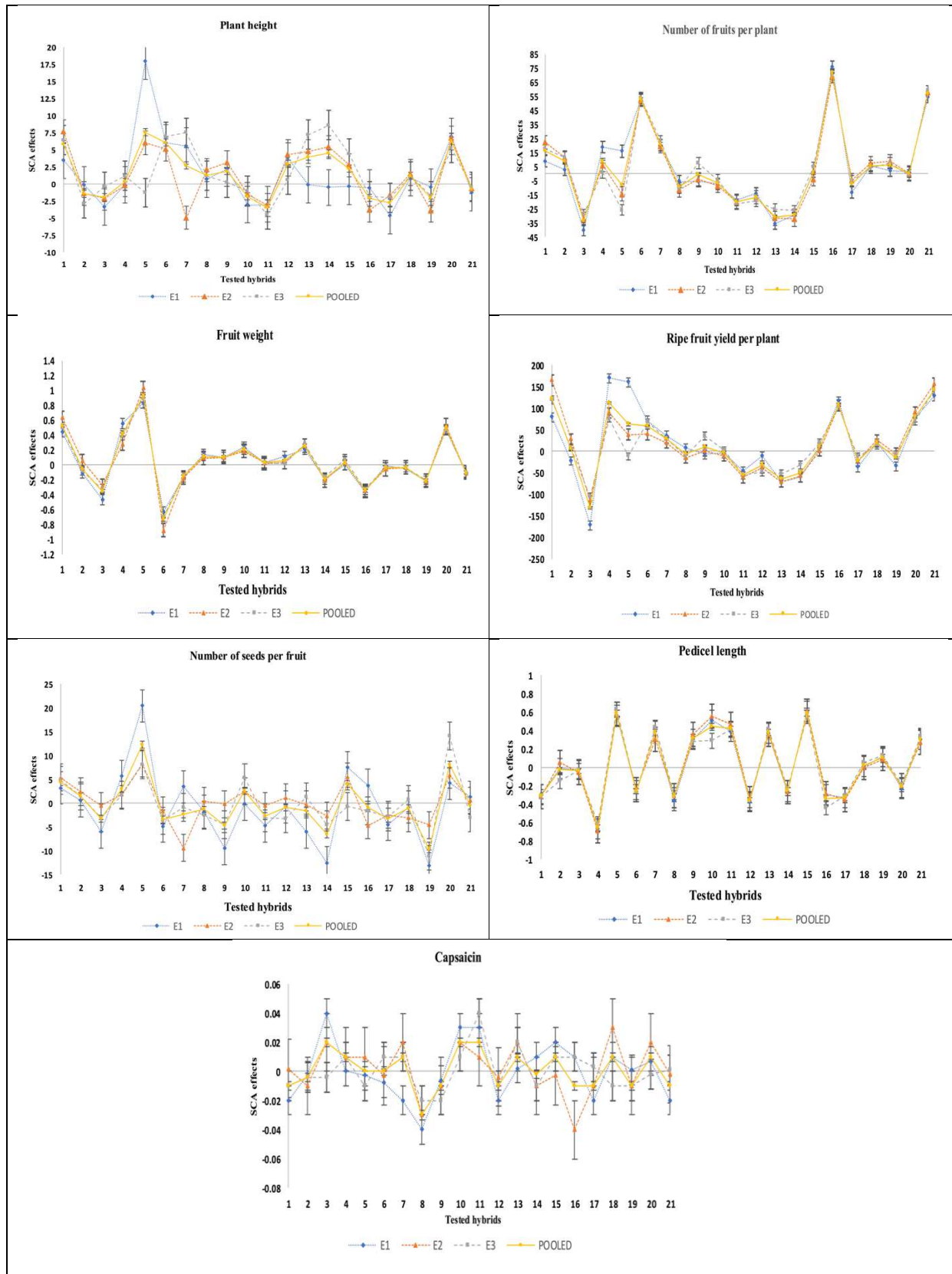


Fig. 3 Specific combining ability (SCA) effects for plant height, number of fruits per plant, fruit weight, ripe fruit yield per plant, pedicel length, number of seeds per fruit and capsaicin.

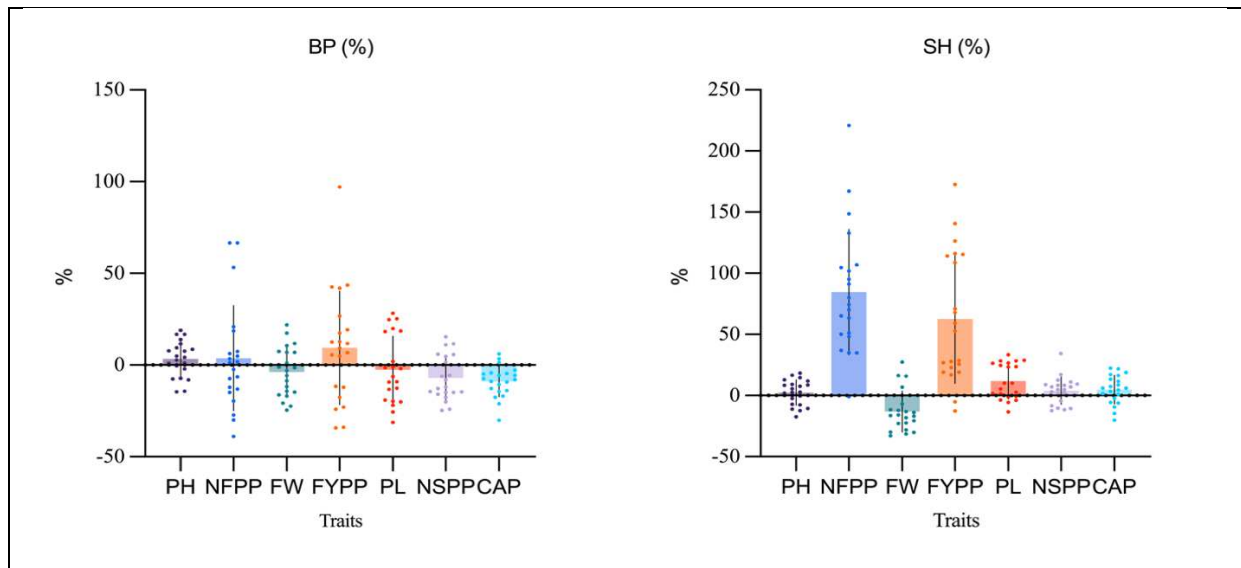


Fig. 4 Pooled heterosis over better parent and standard check for ripe fruit yield per plant, plant height, number of fruits per plant, fruit weight, pedicel length, number of seeds per fruit and capsaicin.

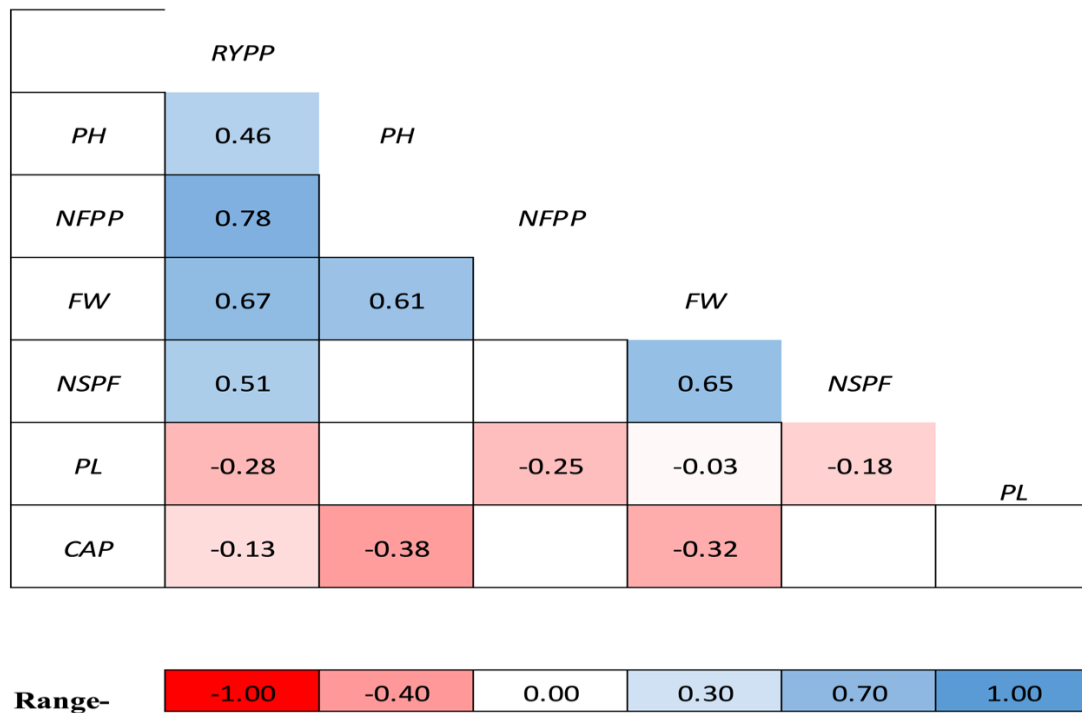


Fig. 5 Pearson's correlation coefficients of red ripe fruit yield per plant and component traits of 21 F_1 's of chilli on the basis of economic heterosis (blue and red circles specify significant positive and negative correlation coefficients, respectively).