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EVALUATION OF CHILLI (*Capsicum annuum* L.) HYBRIDS FOR GROWTH, YIELD AND QUALITY TRAITS

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ABSTRACT

Hybrid evaluation is essential for identifying superior combinations possessing high yield and desirable quality traits for commercial cultivation and future breeding programmes. The present investigation was undertaken to evaluate fifteen experimental chilli (*Capsicum annuum* L.) hybrids developed using MS-12 as the female parent and fifteen diverse male parents. Significant variation was observed among the genotypes for all studied traits. Fruit yield per plant ranged from 620.17 to 1533.65 g among the hybrids, with MS-12 × RS-441 recording the highest yield, followed by MS-12 × SL-468 and MS-12 × DS-175. MS-12 × HM-241 exhibited the highest average fruit weight and total extractable colour, whereas MS-12 × PC-429 recorded the highest capsaicin content in both green and red fruits. Correlation analysis revealed a strong positive association between capsaicin content in green and red fruits ($r = 0.739$), while total fruits per plant showed a strong negative relationship with ascorbic acid ($r = -0.647$), highlighting important trait relationships for selection. Based on overall performance, MS-12 × RS-441, MS-12 × SL-468, MS-12 × DS-175, and MS-12 × HM-241 was identified as promising hybrids for further evaluation and commercial exploitation.

Key words: *Capsicum annuum*, hybrid evaluation, fruit yield, capsaicin, total extractable colour.

Introduction

Chilli (*Capsicum annuum* L.) represents one of the most globally significant spice and vegetable crops, cultivated extensively across tropical and subtropical zones (Anilkumar, 2020). It serves diverse industrial and culinary purposes, utilized as a fresh vegetable, dried condiment, or processed food ingredient, and acts as a vital raw material for the cosmetic, pharmaceutical, and food sectors due to its rich concentrations of capsaicinoids, carotenoids, vitamins, and antioxidants (Bhutia *et al.*, 2015). Beyond its nutritional profile, chilli cultivation supports the livelihoods of numerous farmers and drives the processing industry due to its robust market demand and strong export potential (Rao and Anilkumar, 2020). Consequently, developing high-yielding cultivars while maintaining desirable fruit quality traits has become a primary focus of modern breeding programmes (Chaudhary *et al.*, 2013). India's favorable agro-climatic conditions and extensive genetic diversity make it an ideal

region for chilli cultivation. In 2023–24, Indian markets demonstrated exceptional performance by producing 1.8 million metric tons of chillies, solidifying India's position as the world's largest producer. In Punjab, chilli is grown on an area of 11.40 thousand hectares with a production of 23.09 million tonnes (Anonymous, 2025).

To achieve these goals, the exploitation of hybrid vigour or heterosis has emerged as a highly successful approach for boosting yield and overall productivity in chilli crops (Chaudhary *et al.*, 2013). However, the successful development of elite F1 hybrids depends strictly on selecting appropriate parental lines that possess high combining ability to produce progeny that outperform their parents for key commercial traits. The adoption of male sterility systems simplifies hybrid seed production, reduces labour requirements, and ensures uniformity in F1 hybrids. Punjab Agricultural University has developed high-performing chilli hybrids using genetic and cytoplasmic genetic male sterility systems, such as CH-

1, CH-3, CH-27, and CH-52, which combine high yield potential with resistance to major biotic and abiotic stresses (Dhaliwal *et al.*, 2015, Jindal and Dhaliwal 2021). Even though individual parents might exhibit desirable agronomic traits, their hybrid combinations can display varying degrees of hybrid vigour due to complementary gene action (Nagaraju *et al.*, 2017). Therefore, a systematic and rigorous evaluation of hybrids alongside their parental lines is essential to identify the most commercially viable and promising combinations (Nagaraju *et al.*, 2017). The primary objectives of this research were to compare hybrid performance against parental means, identify superior F₁ combinations, and characterize these promising hybrids based on multiple commercially important attributes to support future varietal development and hybrid breeding programmes.

Material and Methods

The experiment was conducted during 2023–24 and 2024–25 at the Vegetable Research Farm and the Biochemistry Laboratory, Department of Vegetable Science, Punjab Agricultural University, Ludhiana, Punjab. The study consisted of 15 F₁ hybrids by crossing 15 male lines with 1 female line, along with a standard check hybrid, CH-27.

Plant material

The experimental material comprised one female parent (MS-12), fifteen testers, fifteen F₁ hybrids developed through top-cross hybridization, and one standard check variety, resulting in a total of 16 genotypes.

Development of F1 hybrids

The parental lines were raised in well-prepared nursery beds measuring 1.0 m in width and 15 cm in height. Seeds treated with captan at 2–3 g per kg were sown on 15th November 2022 and 2023 at a depth of 1–2 cm under a low tunnel to protect them from low temperature conditions. Before transplanting, seedlings were hardened by withholding irrigation for five days. Transplanting was carried out in the crossing block in the first week of February. A total of 15 crosses were developed by manually pollinating female line MS-12 with 15 male lines (Table 1), ensuring each A-line was crossed with all C-lines. To prevent insect-mediated pollination, parental lines were enclosed in 24-mesh net cages. Manual pollinations were conducted between 8:00 and 11:30 AM by selecting freshly opened flowers of MS-12 (female parents) and dusting them with pollen collected from freshly opened flowers of the respective male parents. For pollen transfer, petals of male flowers were removed to expose the staminal column and anthers, which were gently touched onto the stigmatic surface of the female

Table 1: List of parents and check along with their sources.

Category	Genotypes
Female line	MS-12
Male lines	XC-561, Sel-7-4, SL-480, SL-469, SL-468, SL-485, SL-466, DS-175, PC-434, HM-241, RS-441, PC-430, PC-429, DS-188, HM-242, Punjab Gucchedar
Check hybrid	CH-27

flowers. Pollinated flowers were tagged with the cross details, including date and time of pollination. Mature red fruits were harvested, and seeds were manually extracted.

Evaluation of crosses

During 2023-24 and 2024-25, 15 crosses were evaluated along with their 16 parents and a check hybrid (CH-27). Seedlings were transplanted on ridges with a spacing of 75 cm between rows and 45 cm between plants in February 2024 and 2025, respectively. The experiment employed a randomized complete block design (RCBD) with three replications, each consisting of 10 plants per entry. Standard agronomic practices, including fertilization, irrigation, weed management, and pest and disease control, were followed as per the package of practices for cultivation of vegetable Crops.

Observation recorded:

The data was acquired for numerous growth, yield and quality metrics for assessing the parent and hybrid performances. Height of plants (cm) and spread of plants (cm) were measured during the final fruit harvest. Measurements of fruit length (cm) (FL), fruit width (cm) (FW), and pericarp thickness (PT) were obtained from ten randomly chosen red-ripe fruits from the second harvest. From each of the five chosen plants, ten fruits were gathered, and the average fruit weight was determined. The combined weight of all harvested red fruits at each picking, aligned with their respective stages, was noted and represented in grams per plant.

Quality traits were estimated from each replication in the Biochemistry Laboratory, Department of Vegetable Science, Punjab Agricultural University, Ludhiana.

- **Capsaicin content (%):** Capsaicin was estimated following the method of Bajaj and Kaur (1979). Dried chilli powder was extracted with acetone, purified through an alumina column, and quantified spectrophotometrically at 760 nm using Folin–Ciocalteu reagent. Capsaicin concentration was calculated from a standard curve.
- **Ascorbic acid (mg 100 g⁻¹ FW):** Ascorbic acid content was determined according to the AOAC

(1975) method using metaphosphoric acid extraction and titration with 2,6-dichlorophenolindophenol dye. Results were expressed as mg 100 g⁻¹ fresh weight.

- **Dry matter (%):** Dry matter was determined by oven-drying 100 g of fruit samples at 60 ± 2°C until constant weight and expressed as a percentage of fresh weight.
- **Total extractable colour (ASTA):** Total extractable colour was estimated following the Three Liquid Phase Extraction and Separation (TLPEs) method described by Dang *et al.* (2014). Pigments were extracted with acetone, dipotassium hydrogen phosphate, and *n*-hexane, and absorbance was recorded at 460 nm. ASTA colour value was calculated using the prescribed formula.
- **Oleoresin content (%):** Oleoresin content was determined according to Sen and Houn (2025). Dried chilli powder was extracted with acetone, and the extract was concentrated by solvent evaporation. Oleoresin content was expressed as a percentage of dry weight.

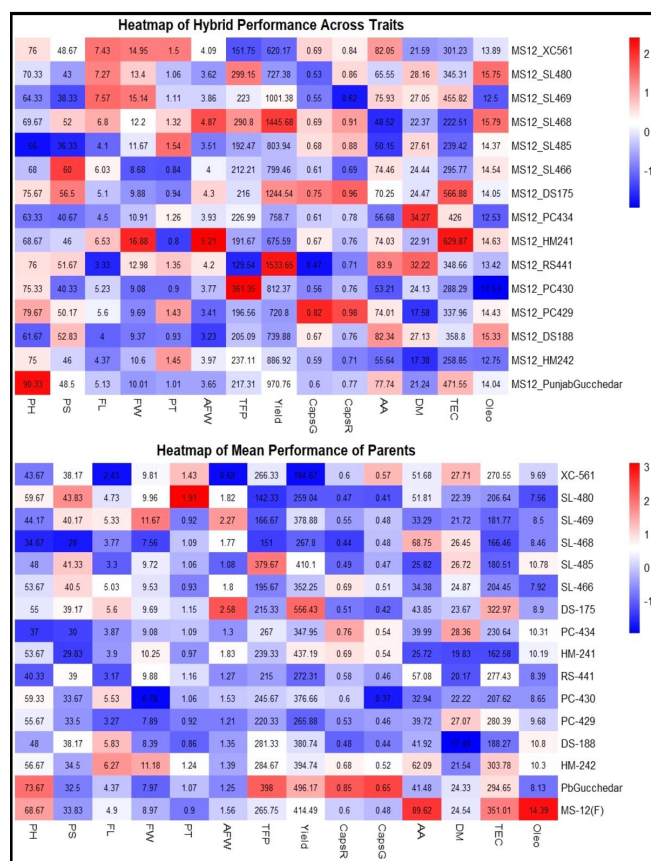


Fig. 1: Heatmap showing the performance of fifteen chilli (*Capsicum annuum* L.) hybrids and their parents for growth, yield, and quality traits.

Table 2: Mixed model analysis of variance for traits.

Trait	F-value	Significance
Plant height (PH)	15.66	***
Plant spread (PS)	4.42	***
Fruit length (FL)	95.34	***
Fruit width (FW)	129.74	***
Pericarp thickness (PT)	14.56	***
Average fruit weight (AFW)	183.61	***
Total fruits per plant (TFP)	760.53	***
Fruit yield per plant (YLD)	575.06	***
Dry matter (DM)	103.20	***
Ascorbic acid (AA)	293.93	***
Total extractable colour (TEC)	647.87	***
Oleoresin (OL)	47.89	***
Capsaicin (Red) (CapRd)	819.19	***

Results and Discussion

Mixed model analysis of variance for traits

The mixed-model analysis of variance revealed significant differences for all 14 traits examined ($p < 0.001$), indicating substantial variation among the genotypes and a wide base of genetic diversity within the evaluated material (Table 2).

Evaluation of parental lines and hybrids for growth, yield and quality parameters

The mean performance of parents and their hybrids for all traits is presented in the Fig. 1.

Growth traits

Significant variation was observed for plant height among the parental lines (34.67–73.67 cm) and hybrids (56.00–90.33 cm). Among the parents, Punjab Guccedar recorded the highest plant height (73.67 cm), whereas SL-468 was the shortest (34.67 cm). The hybrid MS-12 × Punjab Guccedar surpassed both parents with the highest mean plant height (90.33 cm), followed by MS-12 × PC-429 (79.67 cm). Similarly, plant spread ranged from 28.00 to 43.83 cm among parents and from 36.33 to 60.00 cm among hybrids. SL-480 exhibited the

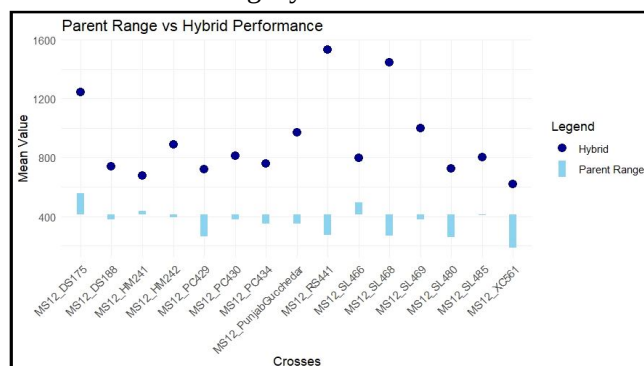


Fig. 2: Comparative performance of chilli hybrids and their parental range for fruit yield.

maximum plant spread among the parents (43.83 cm), while MS-12 × SL-466 recorded the highest value among hybrids (60.00 cm), indicating improved vegetative growth following hybridization.

Fruit traits

Fruit length varied from 2.43 to 6.27 cm among the parents and from 3.33 to 7.57 cm among the hybrids. The longest fruits among the parents were produced by HM-242 (6.27 cm), whereas MS-12 × SL-469 recorded the highest fruit length (7.57 cm). Fruit width ranged from 6.78 to 11.67 mm among parents and 8.68 to 16.88 mm among hybrids. SL-469 was the best parent for fruit width (11.67 mm), while MS-12 × HM-241 recorded the highest hybrid value (16.88 mm). Pericarp thickness varied between 0.86 and 1.91 mm in the parental lines, with SL-480 recording the maximum value (1.91 mm), whereas the hybrid MS-12 × SL-485 exhibited the thickest pericarp (1.54 mm).

Yield traits

Average fruit weight ranged from 0.69 to 2.58 g among parents and from 3.23 to 5.21 g among hybrids. DS-175 recorded the highest fruit weight among the parents (2.58 g), whereas MS-12 × HM-241 produced the heaviest fruits (5.21 g). Total fruits per plant varied from 142.33 to 398.00 among parents, with Punjab Gucchedar producing the maximum number of fruits (398.00g), while MS-12 × PC-430 recorded the highest number among hybrids (361.35g). Fruit yield per plant ranged from 184.67 to 556.43 g in the parents and increased substantially to 620.17–1533.65 g in the hybrids.

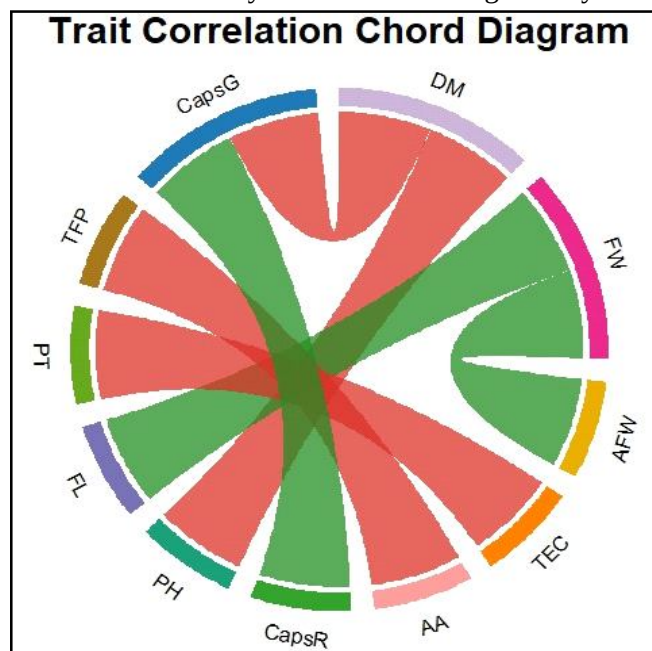


Fig. 3: Chord diagram showing significant correlations among morphological and biochemical traits in chilli hybrids.

The highest parental yield was recorded in DS-175 (556.43 g), whereas MS-12 × RS-441 produced the highest hybrid yield (1533.65 g), followed by MS-12 × SL-468 (1445.68 g) and MS-12 × DS-175 (1244.54 g), demonstrating marked improvement over the parental lines.

Fig. 2 illustrates the relationship between parental performance and hybrid mean performance for fruit yield per plant. In all fifteen crosses, the hybrid mean exceeded the upper limit of the parental range, indicating substantial hybrid vigour over both parents. The parental yield ranged from 267.80 to 272.31 g plant⁻¹, whereas the hybrid MS12 × RS441 produced 1533.65 g plant⁻¹, representing approximately a 5.6-fold increase over the average parental performance. Similarly, MS12 × SL468 yielded 1445.68 g plant⁻¹, which was substantially higher than its parents, indicating considerable hybrid superiority.

Quality traits

Substantial variation was also observed for quality attributes. Capsaicin content in green fruits ranged from 0.44 to 0.85% among parents and from 0.47 to 0.82% among hybrids. Punjab Gucchedar recorded the highest parental capsaicin content (0.85%), while MS-12 × PC-429 exhibited the highest value among hybrids (0.82%). Similarly, red fruit capsaicin varied from 0.37 to 0.65% in the parents and from 0.62 to 0.98% in the hybrids, with MS-12 × PC-429 recording the highest value (0.98%).

Ascorbic acid content ranged from 25.72 to 89.62 mg 100 g⁻¹ FW among the parents, with MS-12 recording the highest value (89.62 mg 100 g⁻¹ FW). Among the



Fig. 4: Promising hybrids identified for yield and horticultural traits.

hybrids, MS-12 × RS-441 recorded the highest ascorbic acid content (83.90 mg 100 g⁻¹ FW). Dry matter varied from 17.49 to 28.36% among parents and from 17.38 to 34.27% among hybrids, with MS-12 × PC-434 recording the highest value (34.27%).

Total extractable colour ranged from 162.58 to 351.01 ASTA in the parental lines and from 222.51 to 629.87 ASTA in the hybrids. The female parent MS-12 recorded the highest parental total extractable colour (351.01 ASTA), while MS-12 × HM-241 produced the highest value among hybrids (629.87 ASTA). Oleoresin content ranged from 7.56 to 14.39% among parents, with MS-12 recording the highest value (14.39%), whereas MS-12 × SL-468 recorded the highest oleoresin content among hybrids (15.79%).

Overall, comparing the parental lines with the hybrids showed that while individual parents contributed valuable traits such as specific growth, yield, or quality characteristics, the hybrids generally outperformed them in most economically significant traits, especially fruit yield, fruit weight, total extractable colour, and oleoresin content, demonstrating the effectiveness of the chosen parental combinations for hybrid development. The results align with Rahayu *et al.*, (2021), Verma *et al.*, (2022), Palled *et al.*, (2024) and Kumar and Singh (2025).

Correlation studies

Pearson's correlation analysis revealed several noteworthy associations among the growth, yield, and biochemical traits (Fig. 3). Among the growth traits, fruit length exhibited a moderate positive association with fruit width ($r = 0.536$) and average fruit weight ($r = 0.313$), while fruit width was also positively correlated with average fruit weight ($r = 0.535$). Plant height showed a moderate negative correlation with dry matter content ($r = -0.520$), whereas plant spread was positively associated with ascorbic acid ($r = 0.451$) and oleoresin content ($r = 0.437$).

Among yield-related traits, average fruit weight was positively associated with fruit yield per plant ($r = 0.363$) and total extractable colour ($r = 0.350$). In contrast, total fruits per plant exhibited a strong negative association with ascorbic acid ($r = -0.647$), indicating that genotypes with higher fruit numbers tended to accumulate lower ascorbic acid levels.

Capsaicin content at the green stage showed a strong positive correlation with capsaicin at the red stage ($r = 0.739$), suggesting consistency in pungency across maturity stages. This agrees with the findings of Bhandari *et al.*, (2013) and Kumar and Tata (2009) and suggests that capsaicin content at the green stage can serve as an

early selection criterion. Oleoresin content was moderately positively associated with capsaicin at the red stage ($r = 0.468$) and average fruit weight ($r = 0.362$). Several negative associations were also observed among quality traits. Capsaicin at the green stage was negatively correlated with dry matter ($r = -0.507$), while pericarp thickness showed a moderate negative association with total extractable colour ($r = -0.567$). Similar observations have been explained by Wubs *et al.*, (2009) and Marcelis *et al.*, (2004) in terms of assimilate partitioning.

Conclusion

The present study demonstrated substantial variability among the evaluated parental lines and hybrids for growth, yield and quality traits. Hybridization resulted in marked improvement in performance over the parental lines, particularly for fruit yield and several economically important quality attributes. Based on the combined assessment of growth, yield and quality parameters, MS-12 × RS-441, MS-12 × SL-468, MS-12 × DS-175, and MS-12 × HM-241 are identified as the most promising hybrids for further multilocation evaluation and potential commercial exploitation. Correlation analysis further demonstrated that several quality traits were closely associated, with capsaicin content showing strong consistency across maturity stages, whereas fruit number exhibited a trade-off with ascorbic acid content. These relationships provide valuable guidance for simultaneous improvement of yield and quality traits in future breeding programmes.

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