



RESEARCH ARTICLE

Perennial growth, yield performance and nutritional quality in interspecific hybrids of *Capsicum frutescens* L. × *Capsicum annuum* L.

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Abstract

Climate change poses an unprecedented threat to global food security, severely impacting the productivity of heat-sensitive crops like chilli, demanding innovative and resilient agricultural interventions. Specifically, temperature extremes and erratic weather patterns severely limit the yield and nutritional stability of globally important spice and vegetable crops like chilli. Traditional breeding programs, while effective, often fall short in developing crops with the broad adaptability required to withstand volatile climatic conditions. This research evaluates the performance of interspecific hybrids of *Capsicum* and their parental lines, *Capsicum frutescens* (P₁) and *Capsicum annuum* (P₂–P₆), demonstrating their potential as a foundational strategy for climate-resilient productivity enhancement. The study was conducted at the College of Agriculture, Vellayani. The study assessed the heterotic performance of five interspecific hybrids (P₁ × P₂, P₁ × P₃, P₁ × P₄, P₁ × P₅ and P₁ × P₆) for yield and quality attributes, positioning these novel genetic combinations as a robust solution to modern agricultural challenges. Hybrids P₁ × P₃, P₁ × P₄ and P₁ × P₆ exhibited superior plant height compared to their parents, a trait linked to enhanced resource capture and stress tolerance. All hybrids, except P₁ × P₂, showed a marked increase in the number of fruits per plant, culminating in superior yield per plant and indicating broad genetic adaptability and resilience to environmental fluctuations. Beyond yield, hybrids P₁ × P₂, P₁ × P₃, P₁ × P₅ and P₁ × P₆ recorded higher vitamin A, while P₁ × P₂ and P₁ × P₄ surpassed their parents in vitamin C content, highlighting improved nutritional traits. All five interspecific hybrids displayed a perennial growth habit, surviving 11 months and outlasting their typically annual parental lines. This prolonged life cycle has the potential to reduce replanting needs and conserve resources, thereby supporting stable farmer income. Overall, the superior yield, quality and perennial nature of these hybrids underscore interspecific hybridisation as a powerful, underutilised tool for breeding climate-resilient, sustainable and nutrition-sensitive capsicum cultivars.

Keywords: capsicum; climate resilience; heterosis; interspecific hybridisation; nutritional quality; perennial growth; yield improvement

Abbreviations: P₁–P₆: Parental lines of *Capsicum*; T₁–T₁₁: Treatments (5 hybrids + 6 parents); F₁: First filial generation hybrids; RBD: Randomized block design; CD (0.05): Critical difference at 5 % significance; SE (m): Standard error of mean; µg: Microgram; mg: Milligram; IU: International units; nm: nanometre; OD: Optical density; DMSO: Dimethyl sulfoxide.

Introduction

Chilli (*Capsicum* spp.) is an economically important vegetable-spice crop cultivated across tropical and subtropical regions, valued for its culinary uses, nutritional compounds and therapeutic properties (1). Among the cultivated species, *Capsicum annuum* remains the dominant type grown worldwide, while *Capsicum frutescens* contributes desirable traits such as high pungency, adaptability and biochemical richness (1). Despite its global relevance, chilli production frequently suffers from low yield potential, primarily due to narrow genetic variability, susceptibility to pests and diseases such as anthracnose, chilli leaf curl virus and bacterial wilt and unstable environmental conditions (2). These limitations have

intensified under contemporary climate uncertainties, reinforcing the necessity for resilient, high-performing cultivars.

Hybrid development is a central strategy for genetic improvement in chilli. The exploitation of heterosis, the phenomenon where hybrid offspring exhibit superior traits compared to their parents, has consistently produced hybrids with superior yield, improved quality and broader adaptability (3). However, the cultivated gene pool of *C. annuum* is often insufficient to sustain long-term enhancement, prompting breeders to draw upon wild relatives such as *C. frutescens* to widen the genetic base (4). Interspecific hybridisation between *C. annuum* and *C. frutescens* has long been recognised as a viable approach for introgressing

favourable alleles related to yield components, nutritional traits, biotic resistance and stress tolerance (5–7). Yet such hybridisation is frequently hindered by incompatibility barriers, hybrid sterility and reduced crossability (3, 7). Techniques such as embryo rescue, somatic hybridisation and reciprocal crossing are often employed to surmount these reproductive obstacles. Overcoming these challenges has been a major focus of *Capsicum* breeding research.

With increasing climatic variability, traits related to resilience such as robust plant architecture, stable fruit set under stress and extended growth duration are gaining importance. In this context, interspecific hybrids have shown promise not only for yield enhancement but also for improving biochemical and adaptive attributes (6, 7). The first experiment of the present study evaluates five F_1 hybrids developed from a cross between *C. frutescens* and diverse *C. annuum* parents, focusing on morphological performance, yield components and key quality traits. The objective is to determine whether these interspecific hybrids express significant heterosis for productivity and nutritional parameters and whether they exhibit adaptive traits including the perennial growth habit observed in the field that may contribute to climate-resilient chilli improvement.

Materials and Methods

Experimental materials

The experiment was conducted as a field study at College of Agriculture, Vellayani, Kerala, India, situated at 8°5' N latitude and 76°9' E longitude and an altitude of 29 m above mean sea level during November 2024–September 2025. This extended 11 month duration validates the perennial growth habit and field persistence of the hybrid progeny.

Five F_1 interspecific hybrids were developed using *Capsicum frutescens* (IC208580) (T_6) as the female parent, selected for its superior cross-compatibility and performance as a female parent in prior evaluations at the Department of Genetics and Plant Breeding, College of Agriculture, Vellayani and five *Capsicum annuum* genotypes-JNTBGRI II (T_7), Unda chilli (T_8), AP-1 (T_9), IC570376 (T_{10}) and Pandalam local 1 (T_{11})-as male parents. The resulting hybrids were designated as $P_1 \times P_2$ (T_1), $P_1 \times P_3$ (T_2), $P_1 \times P_4$ (T_3), $P_1 \times P_5$ (T_4) and $P_1 \times P_6$ (T_5), respectively. These hybrids, along with their six parental lines, formed a total of 11 treatments for evaluation (Table 1 and Fig. 1).

Seeds of the hybrids and parental genotypes were sown in pro-trays filled with a sterilised potting mixture and maintained under a polyhouse environment to ensure uniform germination. Seedlings were transplanted to the field approximately one month after sowing when they attained adequate vigour for establishment.

Table 1. Five F_1 interspecific hybrids and parents

Sl. No.	Treatments		
F ₁ plants			
1	T ₁	P ₁ × P ₂	Capsicum frutescens (IC208580) × Capsicum annuum (JNTBGRI 2)
2	T ₂	P ₁ × P ₃	Capsicum frutescens (IC208580) × Capsicum annuum (Unda chilli)
3	T ₃	P ₁ × P ₄	Capsicum frutescens (IC208580) × Capsicum annuum (AP-1)
4	T ₄	P ₁ × P ₅	Capsicum frutescens (IC208580) × Capsicum annuum (IC570376)
5	T ₅	P ₁ × P ₆	Capsicum frutescens (IC208580) × Capsicum annuum (Pandalam local1)
Parents			
6	T ₆	P ₁	Capsicum frutescens (IC208580)
7	T ₇	P ₂	Capsicum annuum (JNTBGRI 2)
8	T ₈	P ₃	Capsicum annuum (Unda chilli)
9	T ₉	P ₄	Capsicum annuum (AP-1)
10	T ₁₀	P ₅	Capsicum annuum (IC570376)
11	T ₁₁	P ₆	Capsicum annuum (Pandalam local 1)

Experimental design and layout

The field experiment was laid out in a randomized block design (RBD) with 3 replications. Each treatment consisted of a single genotype planted at a spacing of 45 $\times$ 45 cm, following plot preparation that included ploughing, weed removal and incorporation of farmyard manure and the recommended dose of fertilisers. The total number of treatments was 11, comprising 5 F_1 hybrids and 6 parents. All agronomic practices, including irrigation, plant protection and nutrient management, were carried out as per the Kerala Agricultural University package of practices (8). Uniform cultural operations ensured that treatment differences reflected genetic variation rather than management effects.

Biometrical parameters

Observations were recorded from tagged plants during the peak fruiting stage to ensure uniformity in data collection. Plant height was measured in centimetres from the base of the stem to the tip of the main shoot, providing an accurate estimate of vegetative growth. The number of fruits per plant was determined by counting all fruits harvested from each plant throughout the peak fruiting period. Fruit yield per plant, expressed in grams, was calculated by summing the cumulative weight of all fruits harvested from each plant during the productive phase, as shown in Fig. 2 and 3.

Biochemical parameters

The biochemical parameters analysed in the study included vitamin A ($\mu\text{g}/\text{mg}$), vitamin C ($\text{mg}/100\text{ g}$), capsaicin content (%), carotenoid content (mg/g) and anthocyanin content ($\text{mg}/1000\text{ g}$) as shown in Fig. 2 and 3.

Vitamin A content (mg)

5 g of chilli pulp was mixed with 15 mL of acetone along with a few crystals of anhydrous sodium sulphate. The supernatant was decanted and the process was repeated twice. The combined supernatants were transferred to a separating funnel and 10 mL of petroleum ether was added. On standing, the lower transparent layer was collected in a 100 mL volumetric flask and the volume was made up with petroleum ether. Optical density was recorded at 452 nm in a spectrophotometer using petroleum ether as a control. β -carotene was calculated from the calibration curve and was expressed as $\text{mg}/100\text{ g}$ (9).

$$\beta\text{-carotene } (\mu\text{g}/100\text{ mg}) = (\text{O.D} \times 13.9 \times 104 \times 100) / (\text{Weight of sample taken} \times 560 \times 1000) \quad (\text{Eqn.1})$$

$$\text{Vitamin A (IU)} = (\beta\text{-carotene})/0.6 \quad (\text{Eqn. 2})$$

Vitamin C content (mg)

Vitamin C content of the fruit samples was estimated using the 2,6-dichlorophenol indophenol dye method (10). The procedure







Fig. 1. Plant and fruit image of interspecific hybrids and parents. T₁- *Capsicum frutescens* (IC208580) × *Capsicum annuum* (JNTBGRI 2); T₂- *Capsicum frutescens* (IC208580) × *Capsicum annuum* (Unda chilli); T₃- *Capsicum frutescens* (IC208580) × *Capsicum annuum* (AP-1); T₄- *Capsicum frutescens* (IC208580) × *Capsicum annuum* (IC570376); T₅- *Capsicum frutescens* (IC208580) × *Capsicum annuum* (Pandalam local1); T₆- *Capsicum frutescens* (IC208580); T₇- *Capsicum annuum* (JNTBGRI 2); T₈- *Capsicum annuum* (Unda chilli); T₉- *Capsicum annuum* (AP-1); T₁₀- *Capsicum annuum* (IC570376); T₁₁- *Capsicum annuum* (Pandalam local 1).

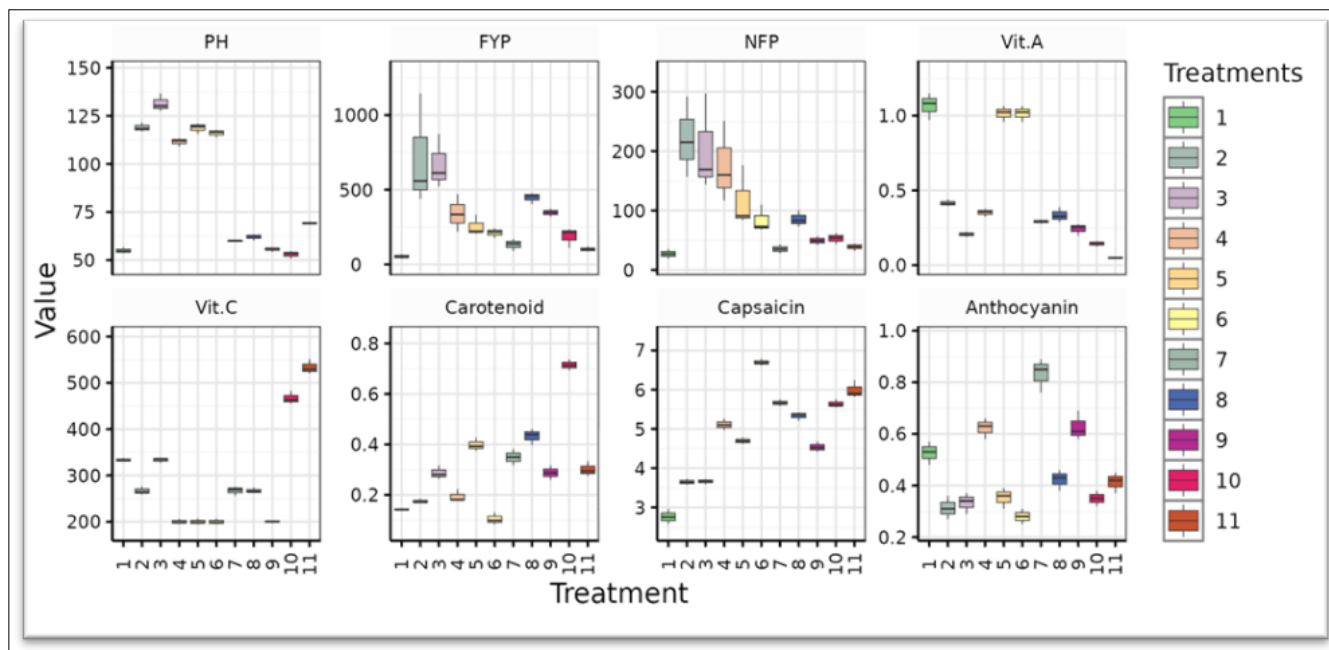


Fig. 2. Box plot on mean performance of yield and quality parameters (PH- Plant height; FYP- Fruit yield per plant; NFP- Number of fruits per plant; Vit. A- Vitamin A; Vit. C- Vitamin C).

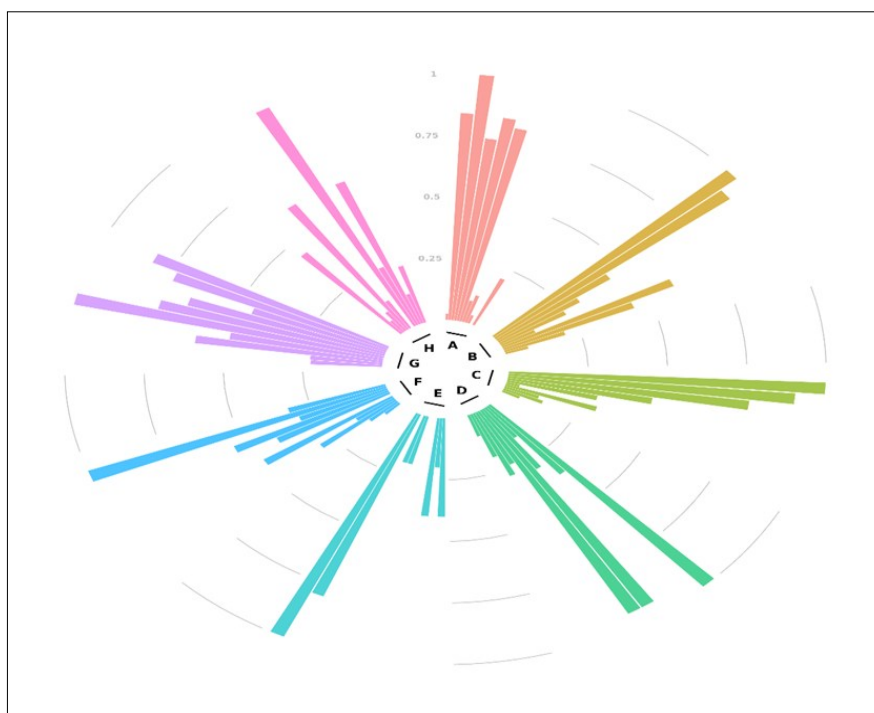


Fig. 3. Radial bar chart on mean performance of yield and quality parameters (A- Plant height; B- Fruit yield per plant; C- Number of fruits per plant; D- Vitamin A; E- Vitamin C; F- Carotenoid content; G- Capsaicin (%); H- Anthocyanin).

involved preparing a series of reagents, beginning with a 4 % oxalic acid solution used both for extraction and dilution. A standard ascorbic acid stock solution was prepared by dissolving 100 mg of ascorbic acid in 100 mL of 4 % oxalic acid, from which a working standard was obtained by diluting 10 mL of the stock to 100 mL with the same oxalic acid solution. The dye solution was prepared by dissolving 42 mg of sodium bicarbonate in a small quantity of distilled water, adding 52 mg of 2,6-dichlorophenol indophenol and making up the volume to 200 mL. The working standard, with a concentration of 100 mg/mL, was then used for standardisation.

For titration, 5 mL of the working standard solution was pipetted into a 100 mL conical flask, followed by the addition of 10 mL of 4% oxalic acid. This was titrated against the dye until a faint pink colour appeared and persisted for at least 5 sec and the dye

volume used (V_1 mL) was recorded. For the sample estimation, 5 g of fresh fruit tissue were extracted in 4 % oxalic acid, filtered and the volume was made up to 100 mL with oxalic acid. From this extract, 5 mL of an aliquot was taken, mixed with 10 mL of 4 % oxalic acid and titrated similarly against the dye to obtain the titre value (V_2 mL). The ascorbic acid content of the sample, expressed as mg/100 g of fruit, was calculated using the formula:

$$\text{Amount of ascorbic acid (mg/100 g)} = (0.5 \times V_2 \times 100) / (V_1 \times 5 \times \text{weight of sample}) \times 100 \quad (\text{Eqn. 3})$$

Carotenoid content (mg)

The carotenoid content of fruit was estimated by the DMSO method. 500 mg of ripe fruit was cut into small bits and placed in a test tube, into which 10 mL of DMSO: 80 % acetone mixture (1:1) was added

and incubated overnight at room temperature. Coloured solution was decanted and by using a measuring cylinder, the volume was made up to 25 mL by adding DMSO - acetone mixture. Absorbance was recorded at 480 and 510 nm using a spectrophotometer. The amount of pigment was calculated by using the following formula and expressed as mg of carotenoid per gram of ripe fruit.

$$\text{Carotenoid} = \frac{(7.6 \times A_{480}) - (1.49 \times A_{510}) \times V}{W \times 1000} \quad (\text{Eqn.4})$$

Capsaicin content

Capsaicin content was determined using the Folin-Denis method, in which the pungency principle of chilli reacts with the Folin-Denis reagent to form a blue-coloured complex that can be quantified colourimetrically (11). For reagent preparation, the Folin-Denis solution was made by refluxing a mixture of 750 mL of distilled water, 100 g of sodium tungstate, 20 g of phosphomolybdic acid and 50 mL of phosphoric acid for two hours, after which it was cooled and the volume was made up to 1 L with distilled water. A 25 % aqueous sodium carbonate solution and acetone were also freshly prepared for use in the assay.

Fruits harvested at the red-ripe stage were dried in a hot air oven at 50 °C and powdered finely using a mixer grinder. From this powder, 500 mg of sample was weighed into test tubes and 10 mL of acetone was added before allowing the mixture to stand overnight for complete extraction of capsaicin. The following day, 1 mL aliquot of the extract was pipetted into a 100 mL conical flask, to which 25 mL of the Folin-Dennis reagent was added. The mixture was kept undisturbed for 30 min. This was followed by the addition of 25 mL of freshly prepared sodium carbonate solution and the contents were shaken vigorously before making up the final volume to 100 mL with distilled water. After allowing the reaction to stand for 30 min, the optical density was measured at 725 nm using a UV-visible spectrophotometer against a reagent blank consisting of acetone, Folin-Denis reagent and sodium carbonate solution in the same proportions.

To prepare the standard curve, a stock solution of pure capsaicin at a concentration of 200 µg/mL was made by dissolving 20 mg of capsaicin in 100 mL of acetone. A series of standard dilutions of known concentrations was then prepared and their absorbance values at 725 nm were recorded. The standard graph obtained from these readings was used to calculate the capsaicin content of the fruit samples, which was expressed as a percentage.

Anthocyanin content (mg)

One gram sample was collected from the ripe fruit. The sample was extracted using ethanolic HCl, filtered through a Whatman No.1 filter paper. The filtrate was then diluted with ethanolic HCl to 50 mL. Absorbance was recorded at 535 nm. The anthocyanin content was calculated using the formula and was expressed as milligrams per gram of the sample (12).

$$\text{Total OD (optical density)/100 g of sample (X)} = \frac{[(\text{absorbance at } 535 \text{ nm}) \times (\text{volume made up for the extract used for colour development}) \times (\text{total volume}) + 100] \times [\text{Volume (mL of extract) used} \times \text{weight of sample taken}]}{98.2} \quad (\text{Eqn. 5})$$

Absorbance of the solution containing 1 mg/mL is equal to 98.2 (content).

$$\text{Total anthocyanin in mg per 100 g of sample} = \frac{X}{98.2} \quad (\text{Eqn. 6})$$

Statistical analysis

GRAPES software was used for the statistical analysis (13). Mean performance of hybrids was compared with that of the parents; CD (0.05) and SE (m) were calculated.

Results

Plant height

The evaluation of plant height revealed considerable variation among the hybrids and their parental lines. Hybrid T₃ recorded the greatest mean plant height (131.49 cm), surpassing the mean values of both its parents, T₆ and T₉. In contrast, the lowest mean plant height was observed in hybrid T₁ (54.99 cm), which was also lower than the corresponding mean values of its parents, T₆ and T₇. Hybrid T₃ differed significantly from all other hybrids in the trial, while T₁₀ showed no significant difference from T₁ and T₉, indicating that these genotypes exhibited comparable plant stature (Table 2).

Number of fruits per plant

A wide range of variation was observed in the number of fruits produced per plant among the hybrids and their parental lines. Hybrid T₂ recorded the highest mean fruit number (221.33), which exceeded the corresponding mean values of both its parents, T₆ and T₈. Hybrid T₁ registered the lowest mean value (27.00), falling below the means of its parental genotypes T₆ and T₇. Hybrid T₂ did not differ significantly from T₃ and T₄, indicating comparable fruit-bearing capacity among these hybrids. Conversely, T₁ was statistically on par with T₆, T₇, T₉, T₁₀ and T₁₁, reflecting similar performance among these treatments for this trait (Table 2).

Fruit yield per plant

Fruit yield per plant showed notable differences among the genotypes evaluated. Hybrid T₂ produced the highest mean yield (714.41 g), surpassing the mean values of both its parental lines, T₆ and T₈. The lowest mean yield was observed in hybrid T₁ (52.47 g), which was also lower than the yields recorded for its parents, T₆ and T₇. Hybrid T₂ was statistically on par with T₃, indicating comparable yield performance between these hybrids. In contrast, T₁ exhibited no significant difference from T₅, T₆, T₇, T₁₀ and T₁₁, reflecting similar yield levels among these treatments (Table 2).

Vitamin A content

Vitamin A content varied considerably among the hybrids and their parental lines. Hybrid T₁ recorded the highest mean value (1.07 mg), surpassing the values of both its parents, T₆ and T₇. In contrast, hybrid T₃ registered the lowest mean value (0.21 mg), which was also lower than the vitamin A content of its parents, T₆ and T₉. Hybrid T₁ was statistically on par with T₅, indicating comparable levels of vitamin A in these treatments, while T₁₁ was found to be on par with (Table 3).

Vitamin C content

Vitamin C content exhibited substantial variation among the treatments. Hybrids T₁ and T₃ recorded the highest mean value (333.50 mg), exceeding the corresponding values of all their parental lines, T₆, T₇ and T₉. Hybrid T₄ showed the lowest mean value (200.09 mg), which was also lower than that of both its parents, T₆ and T₁₀. T₁₁ differed significantly from all other hybrids for this trait. Hybrid T₄ was statistically on par with T₅ and T₉, indicating comparable levels of vitamin C among these treatments (Table 3).

Table 2. Mean performance of hybrids and their parents for biometrical characters

Treatments	Crosses	Plant height (cm)	Number of fruits per plant	Fruit yield/plant (g)
T ₁	P ₁ × P ₂	54.99 ± 1.56 ^f	27.00 ± 8.00 ^d	52.47 ± 14.42 ^e
T ₂	P ₁ × P ₃	118.99 ± 2.36 ^b	221.33 ± 67.72 ^a	714.41 ± 377.34 ^a
T ₃	P ₁ × P ₄	131.49 ± 4.62 ^a	203.33 ± 82.08 ^a	669.86 ± 181.58 ^a
T ₄	P ₁ × P ₅	111.49 ± 2.21 ^c	176.00 ± 68.42 ^a	340.85 ± 125.41 ^{bcd}
T ₅	P ₁ × P ₆	118.67 ± 2.78 ^b	117.00 ± 51.22 ^b	253.75 ± 68.66 ^{bcd}
T ₆	P ₁	115.99 ± 1.99 ^b	83.67 ± 22.94 ^{bcd}	211.66 ± 32.52 ^{cde}
T ₇	P ₂	60.00 ± 0.54 ^e	35.33 ± 7.51 ^{cd}	132.37 ± 40.74 ^{de}
T ₈	P ₃	61.99 ± 1.62 ^e	85.67 ± 14.19 ^{bc}	446.31 ± 37.04 ^b
T ₉	P ₄	55.67 ± 1.16 ^f	49.33 ± 7.51 ^{cd}	347.00 ± 26.68 ^{bc}
T ₁₀	P ₅	52.99 ± 2.00 ^f	53.00 ± 9.54 ^{cd}	187.03 ± 65.87 ^{cde}
T ₁₁	P ₆	69.29 ± 0.69 ^d	38.67 ± 6.11 ^{cd}	102.09 ± 16.63 ^e
CD (0.05)		3.93	56.69	208.91
SE (m)		1.33	19.21	70.82

Different letters represent significant differences at $p < 0.05$ probability level.

Table 3. Mean performance of hybrids and their parents for quality parameters

Treatments	Crosses	Vitamin A (µg/mg)	Vitamin C (mg/100g)	Carotenoid (mg/g)	Capsaicin (%)	Anthocyanin (mg/1000g)
T ₁	P ₁ × P ₂	1.07 ± 0.09 ^a	333.50 ± 3.64 ^c	0.14 ± 0.00 ^{fg}	2.76 ± 0.20 ^g	0.53 ± 0.05 ^c
T ₂	P ₁ × P ₃	0.42 ± 0.02 ^b	266.80 ± 9.14 ^d	0.18 ± 0.01 ^{ef}	3.65 ± 0.08 ^f	0.31 ± 0.05 ^e
T ₃	P ₁ × P ₄	0.21 ± 0.02 ^{ef}	333.50 ± 5.71 ^c	0.29 ± 0.03 ^d	3.66 ± 0.07 ^f	0.33 ± 0.04 ^e
T ₄	P ₁ × P ₅	0.35 ± 0.03 ^{bc}	200.09 ± 5.77 ^e	0.19 ± 0.03 ^e	5.11 ± 0.15 ^d	0.62 ± 0.04 ^b
T ₅	P ₁ × P ₆	1.01 ± 0.05 ^a	200.10 ± 6.50 ^e	0.40 ± 0.03 ^b	4.70 ± 0.08 ^e	0.35 ± 0.04 ^{de}
T ₆	P ₁	1.01 ± 0.05 ^a	266.80 ± 10.59 ^d	0.10 ± 0.02 ^g	6.59 ± 0.07 ^a	0.28 ± 0.03 ^e
T ₇	P ₂	0.29 ± 0.01 ^{cd}	266.93 ± 10.03 ^d	0.35 ± 0.03 ^c	5.67 ± 0.08 ^b	0.83 ± 0.07 ^a
T ₈	P ₃	0.33 ± 0.05 ^c	266.80 ± 6.02 ^d	0.43 ± 0.03 ^b	5.33 ± 0.11 ^c	0.42 ± 0.04 ^d
T ₉	P ₄	0.24 ± 0.04 ^{de}	200.10 ± 2.53 ^e	0.29 ± 0.03 ^d	4.54 ± 0.14 ^e	0.63 ± 0.06 ^b
T ₁₀	P ₅	0.14 ± 0.02 ^f	466.92 ± 13.93 ^b	0.72 ± 0.02 ^a	5.64 ± 0.11 ^b	0.35 ± 0.03 ^{de}
T ₁₁	P ₆	0.05 ± 0.01 ^g	533.62 ± 15.91 ^a	0.30 ± 0.03 ^d	5.99 ± 0.22 ^b	0.41 ± 0.04 ^d
CD (0.05)		0.06	14.51	0.04	0.21	0.08
SE (m)		0.02	4.92	0.01	0.07	0.03

Different letters represent significant differences at a $p < 0.05$ probability level.

Carotenoid content

Carotenoid content varied markedly among the hybrids and their parental genotypes. Hybrid T₅ recorded the highest mean value (0.40 mg), surpassing the values of both its parents, T₆ and T₁₁. In contrast, hybrid T₁ exhibited the lowest carotenoid content, which was also lower than the corresponding values of its parental lines, T₆ and T₇. T₁₀ differed significantly from all other hybrids for this trait. T₆ was statistically on par with T₁, indicating similar carotenoid levels in these treatments (Table 3).

Capsaicin content

Capsaicin content showed considerable variability among the hybrids and parental genotypes. Hybrid T₄ recorded the highest mean value (5.11 %), although this value remained lower than that of both its parents, T₆ and T₁₀. The lowest capsaicin content was observed in hybrid T₁ (2.76 %), which was also lower than the corresponding values of its parental lines, T₆ and T₇. Parent T₆ was significantly different from all hybrids and hybrid T₁ likewise differed significantly from all other treatments evaluated (Table 3).

Anthocyanin content

Anthocyanin content differed noticeably among the treatments. Hybrid T₄ recorded the highest mean value (0.62 mg), surpassing the corresponding values of both its parents, T₆ and T₁₀. The lowest anthocyanin content was observed in hybrid T₂ (0.31 mg), which was lower than its male parent, T₈, but higher than its female parent, T₆. Parent T₇ was significantly different from all other hybrids for this trait. Parent T₆ was statistically on par with T₂, T₃, T₅ and T₁₀, indicating comparable anthocyanin levels among these treatments (Table 3).

Discussion

The interspecific hybrids evaluated in the present study exhibited wide variability for morphological, yield and biochemical traits, reflecting the genetic divergence between *Capsicum frutescens* and *Capsicum annuum* and the complex inheritance patterns associated with interspecific hybridisation. Most notably, all interspecific hybrids exhibited a distinct perennial growth habit, a trait significantly diverging from the annual nature of the parental lines. The superior plant height recorded in the hybrid IC208580 × AP-1 (T₃), which exceeded both parental lines, clearly indicates the expression of positive heterosis for vegetative vigour. Such enhancement in growth is commonly attributed to dominance and over-dominance gene effects operating in wide crosses and has been widely documented in interspecific *Capsicum* hybrids (14). Increased vegetative vigour is often associated with improved photosynthetic efficiency and greater assimilate production, which can contribute to improved yield performance under variable environments (15).

In contrast, the reduced plant height observed in IC208580 × JNTBGRI II (T₁) supports earlier reports of dwarfism in certain interspecific combinations due to genomic imbalance and minor incompatibility effects (16). The contrasting growth responses observed among hybrids in the present study further highlight the strong influence of the male parent on vegetative vigour, with AP-1 (T₉) contributing alleles that enhance plant stature, while JNTBGRI II (T₇) appears to suppress growth. Similar genotype-dependent variation in plant height following interspecific hybridisation has been reported previously (17).

A substantial range of variation was also evident for the number of fruits per plant. Hybrids IC208580 × AP-1 (T₃) and IC208580 × Unda chilli (T₂) produced higher fruit numbers, whereas IC208580 × JNTBGRI II (T₁) recorded the lowest fruit count. Increased fruit number in IC208580 × AP-1 (T₃) may be attributed to higher

branching and early flowering, which together provided a favourable architectural framework for fruit development. Wide variability for fruit number among chilli hybrids has been consistently reported, with elite genotypes producing large numbers of fruits under favourable genetic combinations (18). Enhanced fruit set in interspecific hybrids is frequently associated with heterosis for reproductive vigour, improved pollen function and stable floral retention (19, 20). Conversely, the poor fruiting observed in IC208580 × JNTBGRI II may be related to partial incompatibility or reduced male fertility, which has been linked to post-fertilisation barriers in *C. frutescens* × *C. annuum* crosses (21).

Fruit yield per plant closely followed the trends observed for fruit number. The hybrid IC208580 × Unda chilli recorded the highest yield and consistently outperformed both parents. Yield superiority in this hybrid is likely the cumulative effect of increased branching, higher fruit number, improved fruit development and enhanced vegetative vigour, supporting the classical heterosis model of improved assimilate production and translocation (18, 22). In contrast, the lowest yield recorded in IC208580 × JNTBGRI II (T_1) is consistent with its inferior performance for vegetative and reproductive traits and corroborates earlier findings where certain interspecific hybrids failed to express heterosis due to post-fertilisation barriers (7).

Biochemical traits also showed marked variation among the hybrids. Higher vitamin A content observed in IC208580 × JNTBGRI II (T_1) suggests favourable expression of genes involved in carotenoid biosynthesis, particularly those regulating β -carotene accumulation. Enhanced carotenoid-linked vitamin A content in interspecific chilli hybrids has been associated with increased activity of key enzymes in the carotenoid biosynthetic pathway (23). The contribution of strong carotenoid alleles from *C. frutescens* into *C. annuum* genetic backgrounds has been well documented, while reduced vitamin A levels in certain hybrids may be related to limited pigment accumulation and suboptimal fruit development (24–26).

Vitamin C content also varied significantly among hybrids, with IC208580 × JNTBGRI II (T_1) and IC208580 × AP-1 (T_3) recording higher levels, indicating enhanced antioxidant metabolism. Increased ascorbic acid accumulation in chilli hybrids has been linked to improved fruit physiological maturity, plastid development and elevated activity of the L-galactose biosynthetic pathway (27–29). These observations support the potential of interspecific hybridisation to enhance nutritional quality alongside yield improvement.

Carotenoid content was the highest in IC208580 × Pandalam local 1 (T_5), reflecting strong inheritance of carotenoid regulatory genes from *C. frutescens*. Variation in carotenoid accumulation among hybrids is known to arise from differential expression of enzymes such as capsanthin-capsorubin synthase and other pathway regulators (23, 24). Reduced carotenoid content in weaker hybrids may result from limited plastid differentiation and inefficient pigment biosynthesis (25).

Capsaicin content showed wide variation among hybrids, with IC208580 × IC570376 (T_4) exhibiting the highest pungency, confirming the dominant influence of capsaicinoid biosynthesis alleles contributed by *C. frutescens*. Pungency inheritance in *Capsicum* is primarily governed by the Pun1 gene and associated pathways, which often exhibit non-additive gene action in interspecific backgrounds (30). Lower capsaicin levels in certain

hybrids may be attributed to reduced placenta development or partial incompatibility effects (7, 31).

Anthocyanin content exhibited moderate variation among hybrids, with IC208580 × IC570376 (T_4) showing relatively higher pigmentation. Anthocyanin accumulation in *Capsicum* is regulated by MYB-bHLH-WD40 transcription factor complexes and interspecific allele interactions often result in wide phenotypic variation (32, 33). Reduced anthocyanin levels in some hybrids may reflect suppression of pigment-inducing alleles or recessive gene effects (26, 33).

A particularly important outcome of the present study, consistent with the theme of climate resilience highlighted in the title and abstract, is the perennial growth habit expressed uniformly across all interspecific hybrids. Unlike the predominantly annual parental lines, the hybrids survived and continued to produce across seasons, indicating enhanced longevity and regenerative capacity derived from *C. frutescens*. Perenniality is increasingly recognised as a key adaptive trait that contributes to climate resilience by reducing replanting frequency, improving resource-use efficiency and enabling crops to buffer seasonal climatic fluctuations. In the context of climate-smart agriculture, such perennial interspecific hybrids represent valuable genetic resources for developing resilient and sustainable chilli production systems. Incorporating these perennial hybrids into breeding programs offers a viable pathway for developing low-input, climate-resilient cultivars that align with sustainable agriculture policies.

Conclusion

The study demonstrates that interspecific hybridisation between *Capsicum frutescens* and *C. annuum* effectively broadens the genetic base of chilli, generating hybrids with superior agronomic, biochemical and adaptive traits. Significant variability among hybrids confirmed successful recombination of parental genomes, with T_2 and T_3 showing strong heterosis for yield-related traits, while T_1 , T_4 and T_5 excelled in key nutritional attributes such as vitamins, carotenoids and anthocyanins. A notable and consistent outcome was the introgression of perennial growth habit from *C. frutescens* into all hybrids, conferring enhanced climate resilience, resource-use efficiency and multi-season productivity. Collectively, these results highlight interspecific hybrids as valuable resources for developing climate-resilient and nutritionally enriched chilli varieties, with different hybrids serving distinct breeding objectives. Multi-location and multi-season evaluations, supported by physiological and molecular studies, are required to identify stable, commercially viable cultivars for future climates. Future agricultural policies and breeding initiatives should prioritise the commercial release of these specific *C. frutescens* × *C. annuum* perennial lines to ensure sustainable, year-round chilli production.

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Authors' contributions

RES laid out the experiment, collected the experimental data, carried out the statistical analysis and prepared the manuscript.

SG designed the experiment and provided technical assistance. SS, NSK and PPG assisted in laying out the experiment and contributed to manuscript preparation and correction. All authors have read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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