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Estimation of Heterosis and Heterobeltiosis in Experimental Bell Pepper Hybrids (*Capsicum annuum* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Background: Bell pepper (*Capsicum annuum* L.) breeding can exploit heterosis and heterobeltiosis to identify parental combinations with improved agronomic and fruit-quality performance.
Aims: The objective was to develop and evaluate experimental bell pepper hybrids produced through single plant-to-plant crosses in order to estimate their heterosis and heterobeltiosis.
Study Design: A randomised complete block design was used, comprising sixteen treatments with three replications each; heterosis and heterobeltiosis were estimated using the corresponding formulas.
Place and Duration of Study: Experimental greenhouse "The Bajío", Buenavista, Department of Horticulture, Universidad Autónoma Agraria Antonio Narro, from February 2024 to November 2025.
Methodology: Bell pepper experimental lines in the fifth filial generation (F5)—identified as L1, L6, L9, and L11—were used for crosses. Twelve hybrids, along with the four parents, were generated and evaluated in a greenhouse by quantifying and determining morphological variables, yield, and fruit quality.
Results: Regarding yield, the L9×L1 cross exhibited the highest heterosis and heterobeltiosis values (19.98% and 30.06%, respectively). For the number of fruits per plant, the L9×L1 cross showed the highest heterosis and heterobeltiosis values (21.10 and 3.55, respectively). Regarding average fruit weight, the L6×L9 cross showed heterosis of 23.42 and heterobeltiosis of 55.12. For fruit diameter, the L9×L11 cross achieved the highest heterosis value (12.77) and the highest heterobeltiosis value (17.85); in contrast, for fruit length, the cross with the highest heterosis and heterobeltiosis values was L11×L6 (11.48 and 25.03, respectively).
Conclusions: Genetic divergence exists among the studied populations, as evidenced by the high heterosis and heterobeltiosis values; furthermore, maternal effects significantly influenced the variables under study, indicating the optimal direction for the cross. Consequently, these findings suggest significant variability for developing materials with high productive potential.

Keywords: Bell pepper; Capsicum annuum L.; heterosis; heterobeltiosis; hybrid breeding; reciprocal crosses; fruit yield; fruit quality; parental lines; genetic improvement.

1. Introduction

Bell pepper (*Capsicum annuum* L.) production represents one of the most significant pillars of the Mexican horticultural sector (Moreno-Pérez *et al.,* 2011). Commonly known as "chile morrón" or sweet pepper, this fruit is distinguished by its cubic shape, medium size (approximately 10 cm), and colour transition from green to red, yellow, or orange during ripening (Pathirana, 2013). Bell pepper production is highly profitable due to the crop's high quality and market value; however, ensuring success requires greenhouse cultivation to avoid the climatic limitations associated with open-field farming (Moreno-Pérez *et al.,* 2011). In 2024, the planted area for bell peppers in Mexico totaled 6,586.15 hectares, with 6,584.65 hectares harvested and 2,147.41 hectares exported (Servicio de Información Agroalimentaria y Pesquera, 2024). In recent years, Mexico has established itself as the leading exporter of fresh bell peppers, with the United States, Canada, and the United Kingdom serving as the primary destinations. Statistics indicate very high demand for bell peppers, a factor that drives the development of new varieties or hybrids for the market. Consequently, genetic improvement is essential for producing hybrids that offer higher yields, resistance to pests and adverse weather conditions, and superior nutritional and commercial characteristics (Instituto Nacional de Investigaciones Nucleares, 2018). Global bell pepper breeding efforts primarily focus on Bell and Lamuyo types, specifically red and yellow varieties, addressing quality, yield, and resistance to phytosanitary issues. Crossing, or hybridization, is the primary method of genetic improvement used to obtain new genotypes. Hybridization is defined as the process of crossing individuals with different genetic makeups, aimed at creating new genotypic combinations that possess desirable traits (Goulet *et al.,* 2017; Mwangangi *et al.,* 2019). Hybridization enables the development of cultivars with characteristics superior to existing ones (Mitchell *et al.,* 2019), with the primary goal of creating resilient, efficient varieties that maximise natural resource use and tolerate adverse environmental conditions. The aim is to maximise the yield and quality of the final product while minimising production costs (Mitchell *et al.,* 2019; Qaim, 2020). The market for bell pepper varieties and hybrids is largely dominated by transnational companies responsible for their development and commercialisation (Sánchez-Hernández et al., 2011). Given the limited availability of improved domestic seeds adapted to northeastern Mexico and southeastern Coahuila, this study seeks to identify, through heterosis and heterobeltiosis, hybrids with favourable traits to advance the crop's genetic improvement programme. Recent bell pepper research using male-sterile lines has reported cross-specific differences in mean performance, heterosis, and combining ability for yield-related traits, indicating the importance of evaluating individual parental combinations (Rana et al., 2025). Similarly, heterosis assessment in *Capsicum annuum* has shown variation among F1 combinations for fruit weight and yield-related traits, supporting cross-by-cross evaluation in hybrid breeding (Mule et al., 2026). Recent studies have further assessed *Capsicum annuum* hybrids for heterosis and horticultural traits and have compared newly developed sweet pepper and bell pepper crosses for quality-related characteristics (Ali et al., 2025; Al Kafi et al., 2025; Varsha et al., 2026). Within the breeding programme described in this manuscript, the heterosis and heterobeltiosis of the selected experimental lines in direct and reciprocal crosses had not yet been established under the local greenhouse conditions. Therefore, the objective was to develop and evaluate inter-population bell pepper hybrids via simple plant-to-plant crosses and to estimate their heterosis and heterobeltiosis, thereby determining the genetic potential of the materials selected as parents.

2. Material and Methods

2.1 Location

This project was conducted at the facilities of the Universidad Autónoma Agraria Antonio Narro (UAAAN) in Buenavista, Saltillo, Coahuila, Mexico, using two low-tech greenhouses, one belonging to the Department of Plant Breeding and the other to the

Department of Horticulture. The study utilised four experimental bell pepper lines (designated L1, L6, L9, and L11) at the fifth filial generation (F5); all were obtained through recurrent selection of individual plants and developed at the Seed Technology Training and Development Center (CCDTS) of the UAAAN Department of Plant Breeding.

2.2 Hybrid Formation

The parental lines were sown in 200-cell polystyrene trays, using a germination medium composed of peat moss and perlite in a 70:30 ratio. Sixty-three days after sowing, six seedlings per genotype were selected and transplanted into 10-litre polyethylene pots; two plants were placed in each pot, trained to two stems apiece, and spaced 35 cm apart within a low-tech greenhouse during the January–August 2024 period. Twenty-four plants served as the male parents, and another twenty-four served as the female parents. Nutrition was supplied via drip irrigation and adjusted according to the plant's phenological stage; a Steiner solution was applied with macro- and micro-element concentrations adjusted to 50%, 75%, and 100% levels throughout the crop cycle (**Table 1**). Bell pepper plants produce hermaphroditic flowers; therefore, the plants designated as females were manually emasculated (anthers were removed prior to flower opening). Pollination followed emasculation and was performed manually by cutting a flower from the male parent plant (containing pollen in the anthers) and transferring the pollen to the flowers of the female parent plants. Each female plant was pollinated using pollen from its corresponding male line; this task was carried out between 9:00 AM and 12:00 PM and between 4:00 PM and 6:00 PM over the course of two days, with each pollinated flower labelled to indicate the parent lines used. When the fruits resulting from the crosses reached physiological maturity, they were harvested by hand, and the seeds were manually extracted to prevent mechanical damage; the seeds were placed in a container of water for 6 hours to allow non-viable (empty) seeds to float to the surface, and were subsequently spread on paper at room temperature for 4 days to dry. Once dry, the seeds from each bell pepper fruit were counted and stored in kraft paper envelopes. Finally, the seeds were sown to evaluate the potential of the resulting hybrids.

2.3 Field Establishment and Hybrid Management

The resulting hybrid seed and the parental lines were sown on January 26, 2025, in 200-cell polystyrene trays using a substrate composed of peat moss and perlite in a 70:30 ratio. Field transplanting took place 54 days after sowing in a low-tech greenhouse. Seedlings were established on 30-cm raised beds featuring grey plastic mulch and drip irrigation; the layout consisted of double rows with 1.60 m between beds and 35 cm between plants, resulting in a total density of 37,256 plants ha^{-1}. A randomised complete block design with three replications was used, with each experimental plot consisting of six plants. Crop management followed standard procedures; nutrition was supplied via drip irrigation and adjusted according to the plant's phenological stage, utilising a Steiner solution at concentrations of 50%, 75%, and 100% throughout the crop cycle (Table 1). To prevent and control pests such as whiteflies and thrips, weekly applications of sulfoxaflor, lambda-cyhalothrin, myclobutanil, chlorfenapyr, and imidacloprid + deltamethrin were made to protect the crop; myclobutanil was used against powdery mildew (*Leveillula taurica*) at the manufacturer's recommended dosage.

Table 1. Nutrient solution used during the bell pepper crop cycle

Macroelements										
SN	**Cl-**	**NO_3-**	**H_2PO_4-**	**SO_4^{-2}**	**HCO_3- y CO_3^{-2}**	**K^+**	**Mg^{+2}**	**Ca^{+2}**	**NH_4^+**	**Na^+**
(%)					Miliequivalents L-1					
100	3.2	12	1	7	1	7	4	11	2	3
75	3.2	8.6	0.75	5.2	1	5.2	3	8.2	1.5	3
50	3.2	6	0.5	3.5	1	3.5	2	5.5	1	3
Microelements in parts per million										
SN	**Fe^{+3}**		**Mn^{+2}**	**H_3BO_3**	**Zn^{+2}**	**Cu^{+2}**	**MoO_4^{-2}**	**CE**	**pH**	
(%)								(dS/)		
100	3		1.48	0.28	0.24	0.12	0.08	2.7	5.9-6.1	
75	2.25		1.11	0.21	0.18	0.09	0.06	2.1	5.9-6.1	
50	1.5		0.74	0.14	0.12	0.06	0.04	1.5	5.9-6.1	

2.4 Agronomic Management and Harvesting

During crop development, individual plants were staked using raffia to ensure upright growth, thereby optimising light exposure, ventilation, and space utilization while preventing stem contact with the substrate. Cultivation practices included periodic removal of basal leaves after each harvest to promote aeration and prevent potential infection sites, complemented by continuous manual weeding within the greenhouse for preventive pest control. Finally, the fruits were harvested by hand into plastic containers and transported to the Department of Plant Breeding laboratory for the determination of the evaluated variables.

2.5 Quantification of Variables Related to Fruit Quality, Yield, and Morphology

Total fruit weight was obtained using a Gabatec® digital scale, and yield per hectare (YH) was calculated based on yield per plant and planting density (1.6 m × 0.35 m). Yield data were derived from four harvests: the first at 99 days after transplanting, followed by harvests every 15 days. The number of fruits per plant (NFP) was determined by a total count per plant, and yield per plant (YPP) was based on total fruit weight. Average fruit weight (AFW) was calculated by dividing the total weight by the total number of fruits. Fruit length (FL) and diameter (FD) were measured on four randomly selected fruits per replicate using a Truper® vernier caliper. Total soluble solids (TSS) content was assessed using a Soonda® DT610 automatic refractometer (°Brix), and fruit firmness (FF) was measured with a Fruit Pressure Tester penetrometer (6 mm). Fruit colour (FC) was visually rated on a scale of 1 to 9. Plant height (PH) was measured with a tape measure, while stem thickness (ST) and mesocarp thickness (MT) were measured using a digital caliper. The number of locules (NL) was determined by counting the locules in the harvested fruits.

2.6 Analysis of Results

Heterosis was estimated using the following formula and expressed as a percentage:

$$Heterosis = \frac{F1 - (P1 + P2)/2}{(P1 + P2)/2} * 100$$

Where:

F1 = hybrid from the first cross
P1 = parent one
P2 = parent two

Heterobeltiosis was estimated using the following formula and expressed as a percentage:

$$Heterobeltiosis = \frac{F1 - MP}{MP} * 100$$

Where:

F1 = hybrid from the first cross
MP = the best parent

3. Results and Discussion

Table 2 presents the mean values for seven fruit quality traits evaluated in four experimental bell pepper parental lines (L1, L6, L9, and L11). Differences were observed for most of the evaluated traits, indicating phenotypic variability among the lines. This aligns with studies involving rootstocks, which demonstrated that effects on physical fruit quality parameters (diameter, length, colour, and soluble solids) are significant when interpreting phenotypic variation among experimental parental lines (Sánchez-Chávez et al., 2015). Line L1 stood out for its high values of total soluble solids and fruit length, suggesting fruit with greater sweetness and longitudinal size characteristics that are desirable for the fresh market. Meanwhile, L6 exhibited the greatest fruit diameter and number of locules, attributes associated with higher fruit volume and commercial yield potential. In contrast, L9 showed the highest values for fruit firmness and mesocarp thickness, indicating that these traits are important for resilience during postharvest handling and extended shelf life. Overall, L11 recorded the lowest values for fruit diameter, fruit length, and number of locules, indicating low potential for physical fruit quality compared to the other lines. These results show that each parent possesses specific outstanding attributes, highlighting their potential for use in breeding programmes aimed at developing hybrids with high fruit quality. Comparable greenhouse evaluations of bell pepper genotypes have documented genotype-dependent differences in agronomic performance and fruit-quality attributes, supporting the use of phenotypic variation to identify promising breeding materials (Castañeda et al., 2023).

Table 2. Averages of seven traits evaluated for fruit quality in bell pepper experimental line parents in Saltillo, Coahuila, Mexico

Parents	SST	CF	DF	FF	GM	LF	NL
L1	6.88	7.66	78.59	4.16	5.58	90.55	3.66
L6	6.71	7.66	84.76	3.27	5.83	84.16	4.94
L9	6.22	7.00	72.22	4.61	5.95	73.90	3.44
L11	5.77	7.00	66.26	3.92	5.72	67.70	3.11

L1, L6, L9 y L11= parents; TSS= Total soluble solids; FC= Fruit color; FD= Fruit diameter; FF= Fruit firmness; MT= Mesocarp thickness; FL= Fruit length; NL= Number of locules

Table 3 shows the mean values for six yield-related traits and morphological variables evaluated in four bell pepper experimental line parents (L1, L6, L9, and L11). Parent L11 exhibited the greatest plant height, stem thickness, number of fruits per plant, and yield per hectare, suggesting higher productive capacity and superior vegetative-reproductive vigour. Furthermore, this parent recorded the highest yield per plant, standing out for its superior productive performance. Line L6 excelled in plant height, stem thickness, number of fruits per plant, and yield per hectare, comparable to that of L11, indicating a good balance between vegetative growth and fruit production. Studies on *Capsicum annuum* under protected conditions report significant variability in yield traits, fruit number and weight, plant height, and total yield among the genotypes evaluated (Shrestha *et al.,* 2010). In contrast, L1 was characterized by the highest average fruit weight, albeit with a lower number of fruits per plant and, consequently, lower yield; this suggests that its contribution to yield stems primarily from fruit size. Meanwhile, parent L9 showed the lowest values for plant height, average fruit weight, and yield, reflecting lower plant vigour and, therefore, reduced productive potential. These results demonstrate notable differences among the parents for most of the evaluated traits, indicating broad phenotypic variability with a direct impact on yield, and provide a basis for selecting parents in breeding programmes aimed at increasing bell pepper yield. Similarly, evaluations of bell pepper genotypes under protected cultivation have reported substantial variability in fruit yield and its component traits, reinforcing the importance of exploiting genetic variation when selecting parental material (Prashantha et al., 2026).

Table 3. Means of six traits evaluated for yield and morphological variables in bell pepper experimental line progenitors in Saltillo, Coahuila, Mexico

Parents	PH	ST	NFP	AFW	YPP	YH
L1	106.66	12.63	6.66	180.46	1.20	38.50
L6	136.11	13.85	9.94	174.34	1.73	55.00
L9	69.50	11.06	9.38	109.94	1.03	32.96
L11	147.55	14.69	13.16	143.77	1.86	59.73

L1, L6, L9 y L11= Parents; PH= Plant Height; ST= Stem Thickness; NFP= Number fruits per plant; AFW= Average fruit weight; YH (t ha^{-1})= Yield per hectare; YPP= Yield per plant

3.1 Heterosis

Table 4 presents the results of direct and reciprocal crosses for fruit quality variables; positive heterosis is observed for most variables, with the L6×L11 cross standing out for its positive values in total soluble solids, fruit colour, fruit diameter, fruit firmness, mesocarp thickness, fruit length, and locule number, thereby exhibiting greater heterosis relative to its best parent. Regarding total soluble solids, all crosses showed positive heterosis, but the L11×L9 cross stands out with a heterosis value of 25.59, followed by the L11×L1 and L9×L11 crosses with 19.82 and 15.13, respectively. For fruit colour, the L6×L1 cross stood out with 8.33, followed by the L9×L11 cross with 7.14. The L9×L11 cross achieved the highest heterosis for fruit diameter (12.77) and locule number (15.22), while the L11×L9 cross showed higher heterosis for mesocarp thickness (8.18) and locule number (15.22). For fruit firmness and fruit length, the L11×L6 cross obtained the highest heterosis values, with 34.25 and 11.48, respectively. Variation in the magnitude and direction of heterosis among pepper crosses has also been reported for fruit yield and quality traits, indicating that hybrid responses are strongly dependent on the parental combination (Bhutia et al., 2015).

Table 4. Heterosis of direct and reciprocal crosses in bell pepper for fruit quality-related variables

Crosses	TSS	FC	FD	FF	MT	FL	NL
L11*L9	25.59	-2.38	7.84	0.25	8.18	4.74	15.25
L11*L6	6.31	-4.54	8.13	34.25	4.46	11.48	-4.82
L11*L1	19.82	-4.54	7.41	15.38	13.55	4.13	13.10
L9*L11	15.13	7.14	12.77	15.88	1.99	-0.23	15.25
L9*L6	8.80	2.27	0.64	8.45	-2.77	-4.50	-7.28
L9*L1	9.02	6.81	-1.45	6.33	-0.38	-2.77	4.69
L1*L11	12.28	4.54	-0.38	3.02	-1.47	1.94	6.56
L1*L9	14.61	6.81	-1.79	-1.27	4.81	1.41	0.005
L1*L6	6.86	2.17	-1.79	10.45	-4.13	-6.10	-9.67
L6*L11	6.49	2.27	0.75	9.56	0.91	1.21	0.69
L6*L9	9.31	4.54	1.49	14.08	-1.27	0.11	-8.61
L6*L1	9.87	8.33	-0.16	19.11	0.73	1.59	-6.47

TSS= Total soluble solids; FC= Fruit color; FD= Fruit diameter; FF= Fruit firmness; MT= Mesocarp thickness; FL= Fruit length; NL= Number of locules

Heterosis in a cross generally increases with greater genetic divergence between the parents (Ghaderi *et al.,* 1984). To obtain high-yielding intervarietal hybrids, the parents must be high-yielding and genetically divergent. Table 5 presents the results for direct and reciprocal crosses, showing positive heterosis for certain morphological and yield variables. The L6×L1 cross stands out with positive values across all evaluated variables, exhibiting greater heterosis relative to its parents in traits such as plant height, stem thickness, number of fruits per plant, average fruit weight, yield per plant, and calculated yield per hectare. However, the highest heterosis for yield per hectare was observed in the L9×L1 cross, followed by L6×L1 and L6×L9, a finding consistent with a previous study that demonstrated significant yield-related heterosis (Santiaguillo-Hernández *et al.,* 2004). Regarding the number of fruits per plant, the L9×L1 and L1×L11 crosses stand out, while the L6×L9 cross achieved 24% heterosis for average fruit weight. For yield per plant, the L6×L1 and L6×L9 crosses stand out with values of 17.191 and 16.40, respectively. Regarding morphological variables such as plant height, the L9×L9 cross showed a value of 25.26, followed by the L6×L1 cross with 18.28; for stem thickness, the L6×L9 cross presented the highest value at 6.95. Studies involving hot and sweet pepper hybrids across contrasting environments have likewise reported significant mid-parent heterosis for total yield together with variation in fruit weight, fruit number, and plant traits (Sran & Jindal, 2022).

3.2 Heterobeltiosis

Table 6 presents the results for direct and reciprocal crosses, showing positive heterobeltiosis for most fruit quality variables; specifically, the L11×L6, L11×L1, L9×L11, and L6×L11 crosses exhibited positive values across all evaluated variables, demonstrating superior heterobeltiosis relative to their best parent in traits such as fruit colour, diameter, firmness, mesocarp thickness, length, and number of locules. Regarding total soluble solids and mesocarp thickness, the L11×L1 cross achieved the highest heterobeltiosis, with values of 31.34 and 12.23, respectively. For fruit colour, the L9×L1 and L1×L9 crosses recorded the highest heterobeltiosis value (11.905). Meanwhile, the L11×L6 cross showed the highest values for fruit diameter and length (23.23

and 25.03, respectively). Regarding fruit firmness, the L9×L6 cross achieved a heterobeltiosis value of 30.52, followed by the L9×L11 cross at 26.05. Finally, the L6×L11 cross stood out with the highest percentage for the number of locules (30.36). Heterobeltiosis for fruit-quality and yield-related traits has also been documented in pepper hybrids, with the magnitude and direction of the response differing among hybrid combinations (Bhutia et al., 2015).

Table 5. Heterosis of direct and reciprocal crosses in bell pepper for morphological and yield traits

Crosses	PH	ST	NFP	AFW	YPP	YH
L11*L9	3.76	-0.69	-2.95	4.27	-0.23	-0.23
L11*L6	-0.62	-1.63	5.28	1.49	8.99	8.99
L11*L1	-9.04	-11.09	-5.88	-6.51	-6.23	-6.23
L9*L11	-11.90	-3.14	-8.37	2.32	-8.15	-8.15
L9*L6	0.78	1.20	-5.17	-2.01	-6.03	-6.03
L9*L1	6.52	-0.93	21.10	-7.28	19.98	19.98
L1*L11	-2.57	-5.12	13.72	-10.06	6.99	6.99
L1*L9	10.31	-1.12	-1.03	-3.18	0.49	0.49
L1*L6	-3.43	2.89	10.36	-13.53	-4.13	-4.13
L6*L11	-13.31	-16.19	-24.03	-4.45	-26.18	-26.18
L6*L9	25.26	6.95	-5.17	23.42	16.40	16.40
L6*L1	18.28	4.07	10.87	5.65	17.19	17.19

PH= Plant Height; ST= Stem Thickness; NFP= Number fruits per plant; AFW= Average fruit weight; YH (t ha^{-1})= Yield per hectare; YPP= Yield per plant

Table 6. Heterobeltiosis of direct and reciprocal crosses in bell pepper for fruit quality traits

Crosses	TSS	FC	FD	FF	MT	FL	NL
L11*L9	30.48	-2.38	12.70	9.05	10.38	9.53	21.42
L11*L6	14.90	0.00	23.23	23.22	5.53	25.03	23.21
L11*L1	31.34	0.00	17.40	18.97	12.23	21.70	23.20
L9*L11	19.61	7.14	17.85	26.05	4.07	4.32	21.42
L9*L6	4.88	-2.17	-6.80	30.52	-1.80	-10.33	-21.35
L9*L1	14.80	11.90	2.89	1.20	-3.45	8.18	8.07
L1*L11	23.07	9.52	8.88	6.22	-2.62	19.15	16.08
L1*L9	20.69	11.90	2.53	-6.02	1.58	12.84	3.23
L1*L6	8.27	2.17	-5.37	25.43	-6.18	-2.54	-21.35
L6*L11	15.09	7.14	14.82	0.56	1.94	13.51	30.36
L6*L9	18.05	0.00	-25.47	61.11	-0.83	-25.19	-55.56
L6*L1	11.92	8.69	-3.79	38.99	-1.42	5.49	-17.97

TSS= Total soluble solids; FC= Fruit color; FD= Fruit diameter; FF= Fruit firmness; MT= Mesocarp thickness; FL= Fruit length; NL= Number of locules

Table 7 presents the results for direct and reciprocal crosses, revealing positive heterobeltiosis in most yield-related variables; the L9×L1 cross stands out with positive values across all evaluated variables, exhibiting the highest heterobeltiosis relative to its best parent for average fruit weight (22.45) and total fruit yield (30.06). The L1×L9 (8.94) and L11×L6 (5.13) crosses also showed notable heterobeltiosis for yield. Regarding average fruit weight, the L6×L9 cross stands out with a value of 55.12, followed by L9×L1 with 22.45. The L1×L9 cross exhibited the highest values for the AP and R/P variables, at 39.80 and 8.94, respectively. For stem thickness and number of fruits per plant, L9×L1 showed the highest heterobeltiosis values. Heterobeltiosis varies widely among crosses due to the observed genetic and phenotypic diversity (Camposeco-Montejo et al., 2020) and the genetic divergence between parents (Valdivia-Mares et al., 2016). Evidence from reciprocal *Capsicum* crosses similarly shows that heterosis and reciprocal effects can vary substantially among agronomic and fruit traits, underscoring the importance of evaluating specific parental combinations and cross directions (Naves et al., 2022).

Table 7. Heterobeltiosis of direct and reciprocal crosses in bell pepper for morphological and yield traits

Crosses	PH	ST	NFP	AFW	YPP	YH
L11*L9	-23.68	-12.96	-16.87	-7.99	-22.59	-22.59
L11*L6	-4.48	-4.46	-7.59	12.28	5.13	5.13
L11*L1	-21.64	-17.31	-29.11	5.41	-22.90	-22.90
L9*L11	-35.20	-15.12	-21.51	-9.71	-28.74	-28.74
L9*L6	-23.87	-8.98	-7.82	-20.10	-25.11	-25.11
L9*L1	35.01	6.12	3.55	22.45	30.06	30.06
L1*L11	-16.07	-11.75	-14.34	1.41	-12.02	-12.02
L1*L9	39.80	5.92	-15.38	27.87	8.94	8.94
L1*L6	-13.87	-1.60	-7.82	-12.01	-18.81	-18.81
L6*L11	-16.67	-18.60	-33.33	5.69	-28.79	-28.79
L6*L9	-36.67	-26.38	-38.88	55.12	-6.27	-200.71
L6*L1	6.04	-0.48	-7.82	7.72	-0.83	-0.83

PH= Plant Height; ST= Stem Thickness; NFP= Number fruits per plant; AFW= Average fruit weight; YH (t ha^{-1})= Yield per hectare; YPP= Yield per plant

4. Conclusion

The evaluated F5 bell pepper lines generated direct and reciprocal hybrids with substantial variation in heterosis and heterobeltiosis across yield, morphological, and fruit-quality traits. The L9×L1 cross was particularly notable for yield, with the highest tabulated heterosis and heterobeltiosis values of 19.98 and 30.06, respectively, and it also showed favourable performance for number of fruits per plant. The L6×L9 cross expressed the highest tabulated heterosis and heterobeltiosis for average fruit weight, at 23.42 and 55.12, respectively. For fruit diameter, L9×L11 recorded the highest heterosis (12.77), whereas L11×L6 recorded the highest heterobeltiosis (23.23) and also showed the highest fruit-length heterosis and heterobeltiosis values (11.48 and 25.03). These cross-specific responses indicate that no single parental combination was superior for all evaluated traits. The results therefore provide a basis for selecting experimental hybrids according to the breeding objective, particularly when prioritising yield, fruit size, or fruit-quality attributes. Overall, the observed variation supports continued selection within the existing breeding programme under the evaluated local greenhouse conditions.

5. Limitations

The study evaluated only four F5 parental lines and 12 direct and reciprocal hybrids under greenhouse conditions at a single location, using three replications. Yield estimates were based on four harvests within one production cycle, which may limit assessment of seasonal and environmental variability. The findings are therefore specific to the tested genetic materials and local greenhouse conditions and may not be directly generalisable to other environments or bell pepper populations. Future studies should include a broader genetic base, additional locations and seasons, and repeated evaluations to confirm the stability of heterosis and heterobeltiosis across environments.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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