

Assessing Heterosis and Combining Ability in Bell Pepper (*Capsicum annuum* L.) Using Male Sterile Lines

ABSTRACT

Evolving novel hybrids in bell peppers that satisfy the current market and consumer demand is extremely challenging, therefore development of capsicum hybrids with excellent qualities is the current necessity. In the present study, 15 F₁ combinations were developed by crossing 3 male sterile lines and 5 testers according to line × tester mating design at the Research Farm of Department of Vegetable Science, Dr. YS Parmar University of Horticulture and Forestry, Nauni, Solan and Regional Horticultural Research and Training Station (RHRTS), Dhaulakuan during 2021 and 2022 to assess mean performance, magnitude of heterosis, combining ability, nature and magnitude of gene action for various yield and yield contributing characteristics. On the basis of mean performance and GCA studies, sterile line MS-4 and testers namely, California Wonder and UHF-CAP-27 were found best for majority of characters. MS-4 × UHF-CAP-27 and MS-7 × UHF-CAP-27 were two best cross combinations on the basis of mean performance, specific combining ability and heterosis for majority of the characters under study. Hence, these cross combinations need to be tested in farmers field of mid and low Himalayas.

KEYWORDS: Bell pepper, Heterosis, male sterility, lines, testers, general combining ability, specific combining ability and cross combinations.

1. INTRODUCTION

Bell pepper, also known as sweet pepper, capsicum or Shimla mirch is an important solanaceous vegetable crop. Every species, whether domesticated and wild, is a diploid with chromosomal number $2n=2x=24$. Popularity of bell pepper among consumers is steadily

increasing as a result of their attributes such as wider adaptability, brilliant red, orange and yellow mature fruit color, nutrition, the peculiar fragrance it lends to the food and snackability. Moreover, the consumption of bell pepper has greatly expanded due to the rise in popularity of fast foods and the expansion of the pizza sector (Sood *et al.*, 2011). Bell pepper is one of the most desired off-season vegetable crops in Himachal Pradesh, which gives farmers access to revenue through sales of the produce in neighboring states and large cities (Sharma *et al.*, 2013). It is quite difficult to develop novel bell pepper hybrids that satisfy quality standards including size, shape, colour and non-pungency (Kumari and Sharma, 2014). Choosing high-yield cultivars that are resistant to pests and diseases, protecting them from biotic and abiotic stresses and enhancing the quality, in this case seedlessness and decorative potential of their fruit depending on whether it will be used for industrial or for fresh consumption, is the main challenge. Recombinant breeding should be used to produce high yielding lines with quality attributes in order to fill the gap. Only heterosis breeding can meet the goal of boosting productivity in a short time. Due to customer demand, hybrid breeding that focuses on seedlessness is gaining attention. Hybrid breeding is the quickest way to create seedless cultivars because the F₁ population can be made available to consumers. Accordingly, the current study was designed to assess 15 F₁ combinations, 3 male sterile parental lines and 5 testers with the aim of generating information on the extent of heterosis as well as combining ability for yield and yield-contributing traits.

2. MATERIALS AND METHODS

Five genotypes of bell pepper *viz.*, California Wonder, Solan Bharpur, UHF-CAP-4, UHF-CAP-27 and IIHR-37 used as tester were crossed with three male sterile lines *viz.*, MS-4, MS-6 and MS-7 in line \times tester mating design suggested by Kempthorne (1957) to obtain fifteen F₁ combinations during 2021. During summer season, (March, 2022) plants of three male sterile lines, five testers and fifteen F₁ hybrids along with standard check (Bharath) were transplanted under open conditions in randomized block design with three replications for their comparative evaluation. The observations were recorded on randomly selected plants for various characteristics namely, days to fifty per cent flowering, days to marketable maturity, plant height (cm), plant spread (cm), number of primary branches, fruit length (cm), fruit diameter (cm), average fruit weight (g), number of lobes per fruit, pericarp thickness (mm), number of fruits per plant, fruit yield per plant (g) and harvest duration (days). The heterosis over better parent and

standard check was estimated using standard formula and analyses were carried out using TNAU STAT computer software programme.

The following formula was followed for the calculation of different estimates of heterosis:

- (i) Heterosis over better parent (%) = $[(\bar{F}_1 - \bar{BP})/\bar{BP}] \times 100$
- (ii) Heterosis over standard check (%) = $[(\bar{F}_1 - \bar{SC})/\bar{SC}] \times 100$

3. RESULTS AND DISCUSSION

3.1 Heterosis studies

Per cent heterosis over better parent and standard check (Bharath) has been elucidated in Table 1 and 2. Earliness is one of the most desirable characters for bell pepper from an economic standard point due to high market price in early season which was indicated by days to fifty per cent flowering and days to marketable maturity and the crosses with negative significant heterosis were considered as desirable for this characteristic. Earliness in bell pepper hybrids due to a negative heterotic effect of a considerable amount was reported earlier by Kaur (2016).

Biologically plant height reflects the rate of vegetative development in crops, defined as the sum of internode lengths above ground (Shang *et al.*, 2015). Patil *et al.* (2012) observed -22.68 per cent to 7.75 per cent better parent heterosis and Sharma *et al.* (2013) -9.24 per cent to 18.74 per cent standard heterosis.

Likewise, Heterosis for plant spread character was also reported earlier by Shankarnag and Madalageri (2006) where heterosis ranged from -37.83 per cent to 51.85 per cent over better parent and -21.60 to 55.61 per cent over standard check.

For number of primary branches, Similar results were observed by Yadahalli (2016) where better parent heterosis varied from -30.30 per cent to 17.86 per cent and standard heterosis from -17.86 per cent to 17.86 per cent.

In terms of fruit length,. Bilashini (2014) who reported better parent and standard heterosis varied from -29.42 percent to 28.29 per cent and -12.61 per cent to 36.31 per cent, respectively. Seneviratne and Kannangara (2004) also reported negative standard heterosis earlier for fruit diameter.

Table 1: Estimation of heterosis over better parent and standard check in bell pepper

Sr. No.	Crosses	Days to 50% flowering		Days to marketable days		Plant height (cm)		Plant spread (cm)		Number of primary branches		Fruit length (cm)		Fruit diameter (cm)	
		BP	Check	BP	Check	BP	Check	BP	Check	BP	Check	BP	Check	BP	Check
1.	MS-4 × California Wonder	2.5	-17.46*	1.52	-14.83*	0.36	29.70*	-5.80*	27.90*	0.46	17.33*	1.89	-3.84	- 18.35*	- 12.66*
2.	MS-4 × Solan Bharpur	3.25	6.70*	1.32	-0.85	-3.45	24.77*	-9.52*	22.84*	6.85	22.67*	12.21*	- 10.62*	-0.79	- 16.42*
3.	MS-4 × UHF-CAP-4	0.01	-18.80*	-1.51	-16.95*	-0.84	28.14*	- 10.81*	21.09*	17.44*	40.93*	6.45*	-4.95*	4.81	- 10.89*
4.	MS-4 × UHF-CAP-27	- 14.81*	-22.82*	-9.86*	-18.65*	5.70*	36.60*	-5.74*	27.98*	-1.02	16.00*	10.79*	3.53	17.61*	-2.16
5.	MS-4 × IIHR-37	- 17.01*	-18.13*	- 15.81*	-16.53*	-1.25	27.61*	-8.28*	24.53*	-0.11	18.67*	5.99*	6.56*	- 14.77*	- 14.48*
6.	MS-6 × California Wonder	0.83	-18.80*	-2.53	-18.22*	-5.75*	24.25*	-0.25	28.41*	7.29	37.33*	10.83*	4.60*	- 13.91*	-7.96*
7.	MS-6 × Solan Bharpur	5.85*	9.39*	6.94*	4.66*	3.38	36.28*	6.59*	37.22*	2.08	30.67*	8.21*	- 14.68*	-7.75*	- 22.33*
8.	MS-6 × UHF-CAP-4	24.80*	1.34	16.08*	-2.12	-1.61	29.71*	2.82	32.36*	-12.19*	12.40*	8.60*	-3.03	7.09*	-8.96*
9.	MS-6 × UHF-CAP-27	9.63*	-0.68	7.97*	-2.56	- 28.13*	-5.26*	- 15.71*	8.51*	-1.04	26.67*	-6.02*	- 12.18*	1.46	- 15.59*
10.	MS-6 × IIHR-37	-2.72	-4.03	-2.13	-2.96	-8.94*	20.04*	-5.49*	21.67*	5.21	34.67*	1.24	1.78	-2.15	-1.82
11.	MS-7 × California Wonder	4.17	-16.11*	2.53	-13.99*	-4.63*	24.37*	-0.97	22.80*	-3.07	30.67*	13.38*	7.01*	- 12.87*	-6.85*
12.	MS-7 × Solan Bharpur	-1.94	1.34	2.20	-1.70	-0.72	29.47*	3.14	21.70*	4.85	41.33*	-0.23	- 21.06*	-0.59	- 16.31*
13.	MS-7 × UHF-CAP-4	5.79	-14.10*	3.52	-12.72*	1.52	32.39*	-3.97*	21.84*	-11.97*	18.67*	20.49*	7.59*	9.82*	-6.63*
14.	MS-7 × UHF-CAP-27	0.00	-9.40*	0.00	-9.75*	5.23*	37.22*	10.65*	30.21*	-22.85*	4.00	16.24*	8.61*	19.00*	-1.00
15.	MS-7 × IIHR-37	- 14.97*	-16.11	-7.93*	-11.44*	- 20.30*	3.93	-7.92*	8.36*	-23.84*	2.67	18.06*	18.70*	-0.66	-0.33

Table 2: Estimation of heterosis over better parent and standard check in bell pepper

Sr. No.	Crosses	Average fruit weight (g)		Number of lobes per fruit		Pericarp thickness (mm)		Number of fruits per plant		Fruit yield per plant (g)		Harvest duration (days)	
		BP	Check	BP	Check	BP	Check	BP	Check	BP	Check	BP	Check
1.	MS-4 × California Wonder	-27.01*	-24.87*	-18.88*	-25.16*	1.63	0.78	-28.96*	21.51*	11.59*	-8.73*	17.53*	13.13*
2.	MS-4 × Solan Bharpur	1.34	-46.02*	-8.74*	-30.40*	8.12*	-3.31	-0.27*	70.55*	12.56*	-7.94*	7.36*	9.38*
3.	MS-4 × UHF-CAP-4	-19.35*	-28.70*	-5.44*	-18.04*	-5.93*	-10.50*	-19.64*	37.41*	16.00*	-2.02	5.77*	3.13
4.	MS-4 × UHF-CAP-27	-8.86*	-18.51*	6.82*	-12.27*	5.62*	-0.63	-31.81*	16.62*	16.19*	-4.97*	14.47*	13.76*
5.	MS-4 × IIHR-37	-3.91*	-12.14*	-17.13*	-27.27*	5.83*	-5.63*	-16.46*	42.86*	36.07*	25.52*	-4.85*	-1.87*
6.	MS-6 × California Wonder	-10.76*	-8.14*	-17.24*	-23.64*	5.05*	4.16*	-30.04*	5.83*	30.97*	-2.78	2.58*	-0.62*
7.	MS-6 × Solan Bharpur	-10.09*	-52.11*	-19.93*	-38.93*	1.06	-12.40*	7.58*	62.75*	6.27*	-22.06*	-6.75*	-4.99
8.	MS-6 × UHF-CAP-4	0.16	-11.44*	-15.28*	-26.58*	6.67*	1.48	0.09	51.41*	58.74*	34.08*	19.23*	16.26*
9.	MS-6 × UHF-CAP-27	-37.28	-43.93*	-18.83*	-33.33*	2.25	-3.81	-26.10*	11.79*	-14.36*	-37.33*	13.21*	12.51*
10.	MS-6 × IIHR-37	12.80*	3.14*	3.98	-9.33*	19.12*	2.75	-21.18*	19.24*	33.33*	22.99*	3.03	6.26*
11.	MS-7 × California Wonder	-19.86*	-17.51*	-22.64*	-28.62*	10.66*	9.73*	-29.87*	8.29*	20.31*	-10.69*	-9.66*	-0.62
12.	MS-7 × Solan Bharpur	3.92	-44.65*	-9.44*	-30.93*	2.35	-7.82*	-20.08*	23.42*	-6.86*	-31.69*	-0.57	9.38*
13.	MS-7 × UHF-CAP-4	-7.57*	-18.28*	-12.00*	-23.73*	-5.11*	-9.73*	-15.67*	30.22*	25.99*	6.42*	-9.66*	-0.62
14.	MS-7 × UHF-CAP-27	12.60*	0.67	7.14*	-12.00*	5.84*	-0.42	-19.28*	24.65*	72.19*	25.52*	-1.14*	8.76*
15.	MS-7 × IIHR-37	11.64*	2.09	-14.58*	-25.51*	0.78	-9.23*	-44.24*	-13.90*	-4.71*	-12.10*	3.98	5.63*

Similarly, Hegde *et al.* (2019) noted heterosis over better parent ranged -34.48 per cent to 27.46 per cent and -50.08 per cent to 7.21 per cent over standard check.

Similar observations were reported by Kumar (2009) where, standard heterosis ranged from -41.67 per cent to 0.00 per cent for number of lobes per fruit.

Pericarp thickness has a strong correlation with the firmness of the fruits. Rao *et al.* (2016) likewise reported heterosis of similar magnitude, ranging from -18.18 percent to 16.67 percent over the superior parent and -28.57 percent to 11.11 percent over the standard check.

For number of fruits per plant, MS-6 \times Solan Bharpur was the only cross combination reported with significant positive heterosis over better parent. Roy *et al.* (2018) also noted -37.9 per cent to 4.09 per cent heterosis over better parent for this character. MS-4 \times Solan Bharpur followed by MS-6 \times Solan Bharpur showed maximum standard heterosis.

For fruit yield per plant, MS-7 \times UHF-CAP-27 and MS-6 \times UHF-CAP-4 showed maximum positive heterosis over better parent whereas, MS-6 \times UHF-CAP-4 followed by MS-4 \times IIHR-37 displayed maximum standard heterosis.

Greater emphasis is laid on a genotype having longer harvest period as it contributes to a higher marketable yield in bell pepper. For harvest duration, MS-6 \times UHF-CAP-4 and MS-4 \times California Wonder revealed positive heterosis over better parent while, cross combinations namely, MS-6 \times UHF-CAP-4 and MS-4 \times California Wonder reported highest standard heterosis over standard check Bharath. The present investigation concurs with Bilashini (2014) findings, which indicate outstanding heterosis ranging from -22.43 percent to 19.94 percent over the better parent and -20.26 percent to 35.74 percent over standard check.

3.2 Estimates of general combining ability effects of parents and specific combining ability effects of crosses for earliness

For days to 50 per cent flowering (Table 3), among Testers, California Wonder, IIHR-37 displayed substantial negative GCA effects although, Solan Bharpur had significant positive values indicating that these were good and poor general combiners, respectively. While, among lines, MS-4 and MS-7 were good general combiners. Yadahalli (2016) reported significant GCA effects in the parent California Wonder (-4.44) for days to fifty per cent flowering. Out of fifteen crosses, two cross combinations *viz.*, MS-6 \times California Wonder and MS-4 \times UHF-CAP-27 involving parents with poor \times good and good \times average general combiningability respectively

Table 3: Estimation of general combining ability (GCA) effects of parents for different characteristics in bell pepper

Parent(s)/ Character	Days to fifty per cent flowering	Days to marketable maturity	Plant height (cm)	Plant spread (cm)	Fruit length (cm)	Fruit diameter (cm)	Number of primary branches
Line(s)							
MS-4	-2.44 *	-3.40*	2.17*	0.45	-0.08	-0.10*	-0.01
MS-6	3.29*	3.93*	-2.28*	0.79*	-0.29*	-0.10*	0.12*
MS-7	-0.84*	-0.53	0.10	-1.24*	0.37*	0.21*	-0.10*
S.E. (gi) Lines	0.39	0.58	0.46	0.36	0.05	0.04	0.04
S.E. (gi-gj) Lines	0.56	0.82	0.64	0.51	0.06	0.05	0.06
C.D. _(0.05) (gi) Lines	0.81	1.18	0.93	0.74	0.09	0.07	0.09
C.D. _(0.05) (gi-gj) Lines	1.14	1.68	1.32	1.05	0.13	0.10	0.12
Tester(s)							
California Wonder	-4.11*	-5.07*	0.44	1.11*	0.25*	0.03	0.12*
Solan Bharpur	7.44*	7.82*	2.60*	1.49*	-1.09*	-0.53*	0.20*
UHF- CAP-4	-0.67	-1.07	2.55*	0.55	0.05	0.05	0.01
UHF-CAP-27	-0.89	-0.85	-1.29*	-0.70	0.06	0.20*	-0.20*
IIHR-37	-1.78*	-0.84	-4.30*	-2.45*	0.73*	0.25*	-0.12*
S.E. (gi) Testers	0.51	0.75	0.59	0.47	0.06	0.05	0.05
S.E. (gi-gj) Testers	0.72	1.06	0.83	0.66	0.08	0.07	0.08
C.D. _(0.05) (gi) Testers	1.04	1.53	1.20	0.95	0.12	0.09	0.11
C.D. _(0.05) (gi-gj) Testers	1.47	2.16	1.70	1.35	0.17	0.13	0.16

Table 4: Estimation of general combining ability (GCA) effects of parents for different characteristics in bell pepper

Parent(s)/ Character	Average fruit weight (g)	Number of lobes per fruit	Pericarp thickness (mm)	No. of fruits per plant	Fruit yield / plant (g)	Harvest duration (days)
Line(s)						
MS-4	-4.38*	0.06*	-0.04	1.06*	20.11*	0.82
MS-6	-1.06*	-0.07*	0.07*	0.28*	6.72	-0.04
MS-7	5.45*	0.01	-0.03	-1.33*	-26.84*	-0.78
S.E. (gi) Lines	0.47	0.02	0.03	0.07	5.52	0.44
S.E. (gi-gj) Lines	0.67	0.03	0.04	0.10	7.80	0.63
C.D. _(0.05) (gi) Lines	0.97	0.04	0.06	0.14	11.30	0.91
C.D. _(0.05) (gi-gj) Lines	1.37	0.06	0.09	0.20	15.99	1.28
Tester(s)						
California Wonder	4.23*	-0.05	0.37*	-1.61*	-54.68*	-1.07
Solan Bharpur	-24.53*	-0.34*	-0.23*	2.54*	-181.29*	-0.73
UHF- CAP-4	1.76*	0.06*	0.16*	1.25*	139.96*	0.16
UHF-CAP-27	0.72	0.20*	0.06	-1.01*	-37.28*	3.04*
IIHR-37	17.82*	0.13*	-0.05	-1.18*	133.29*	-1.40*
S.E. (gi) Testers	0.61	0.03	0.04	0.09	7.12	0.57
S.E. (gi-gj) Testers	0.86	0.04	0.06	0.13	10.07	0.81
C.D. _(0.05) (gi) Testers	1.25	0.06	0.08	0.18	14.59	1.17
C.D. _(0.05) (gi-gj) Testers	1.76	0.08	0.11	0.26	20.64	1.66

was found to be good specific combiners due to their negative specific combining ability effects. Kaur *et al.*, 2018 reported significant SCA effects in the cross UHF-8 \times California Wonder (-4.06) in their study for days to fifty per cent flowering.

In addition to early flowering, early maturity of the fruit is just as crucial as early blossoming because a difference of a few days in marketing can have a major impact on the grower's earnings. In the present study, MS-4 line was a good general combiner with significant negative GCA effects, while MS-6 was a poor general combiner and MS-7 was average combiner for days to marketable maturity. Significant negative GCA effects was exhibited by tester California Wonder and was indicated as good, while Solan Bharpur was elected as poor general combiner and remaining testers were average general combiners. Rekha, 2016 reported significant GCA effects in the parent LCA 764 for days to marketable maturity. Out of fifteen crosses studied, significant negative specific combining ability effects were exhibited by only two cross combinations i.e., MS-6 \times California Wonder (-5.93) and MS-4 \times UHF-CAP-27 (-3.15) with parents of poor \times good and good \times average GCA effects respectively. Kaur *et al.*, 2018 also reported significant SCA effects in the cross UHF-11 \times Solan Bharpur (-5.00) in their study.

3.3 Estimates of general combining ability effects of parents and specific combining ability effects of crosses for horticultural characteristics.

Among lines MS-4 was good general combiner and MS-6 was poor combiner for plant height whereas, MS-7 line was regarded as average general combiner. Amongst the five testers used in the investigation, Solan Bharpur and UHF-CAP-4 were observed as good general combiners whereas; IIHR-37 and UHF-CAP-27 were observed as poor general combiners. California Wonder was the only tester found to be an average general combiner for plant height. Out of fifteen cross combinations, five cross combinations *viz.*, MS-7 \times UHF-CAP-27, MS-6 \times Solan Bharpur, MS-4 \times UHF-CAP-27, MS-6 \times IIHR-37 and MS-4 \times IIHR-37 were good specific combiners due to significant positive SCA effects; these crosses involved the parents either with average \times poor, poor \times good, good \times poor, poor \times poor, good \times poor GCA effects.

For plant spread, only MS-6 line stood out among the others as a good general combiner whereas, line MS-7 was deemed as a poor general combiner. MS-4 was recognized as average general combiner for plant spread. Solan Bharpur and California Wonder were two testers

regarded as good general combiners for this character. IIHR-37 was poor general combiner and the remaining 2 testers were observed as average combiners for plant spread. Among the cross combinations, good specific combiners were MS-7 \times UHF-CAP-27, MS-6 \times Solan Bharpur, MS-6 \times UHF-CAP-4, MS-4 \times IIHR-37 and MS-4 \times UHF-CAP-27 with significant SCA effects. Parents poor \times average, good \times average, average \times poor and average \times average was involved in these cross combinations. Rekha *et al.*, 2016 reported significant SCA effects in the cross LCA 764 \times LCA 763 (4.97) for plant spread.

For number of primary branches, MS-6 was regarded as a good general combiner, while MS-7 was a poor general combiner and MS-4 was average general combiner. Two testers viz., Solan Bharpur and California Wonder had good general combining abilities (Aditika, 2018 reported Solan Bharpur as good general combiner due to positive values of GCA effects) whereas, UHF-CAP-27 and IIHR-37 testers had poor general combining abilities for the character under study and UHF-CAP-4 was identified as average general combiner. For this character, three F₁ combinations MS-4 \times UHF-CAP-4, MS-7 \times Solan Bharpur and MS-6 \times IIHR-37 showed significant positive SCA effects, therefore were assessed to be good specific combiners. These F₁ combinations parents had average \times average, poor \times good and good \times poor general combining effects. The outcomes correspond with Yadahalli (2016), who revealed significant SCA impacts in the number of primary branches of the cross Arka Mohini and Yolo Wonder (0.21).

For fruit length, the line MS-7 was the best general combiner and MS-6 had poor general combining ability, whereas MS-4 had average general combining ability. Out of the five testers, IIHR-37 and California Wonder were good general combiners, whereas Solan Bharpur was a poor general combiner for this character. Hegde *et al.*, 2019 reported significant positive GCA effect in the parent EC802552 (1.94) for fruit length. However, non-significant GCA effects were found in UHF-CAP-27 and UHF-CAP-4. Out of the fifteen cross combinations, five combinations namely MS-4 \times Solan Bharpur (average \times poor), MS-4 \times California Wonder (average \times good), MS-7 \times IIHR-37 (good \times good), MS-4 \times UHF-CAP-27 (average \times average) and MS-7 \times UHF-CAP-27 (good \times average) expressed significant positive specific combining ability effects.

Table 5: Estimation of specific combining ability (SCA) effects of crosses for different characteristics in bell pepper

Cross(s) / Character	Days to fifty per cent flowering	Days to marketable maturity	Plant height (cm)	Plant spread (cm)	Fruit length (cm)	Fruit diameter (cm)	Number of primary branches
MS-4 × California Wonder	2.44*	4.07*	-0.26	0.21	-0.40*	-0.11	-0.26*
MS-4 × Solan Bharpur	2.89*	2.18	-5.05*	-2.37*	0.44*	0.22*	-0.21*
MS-4 × UHF- CAP-4	-1.67	-1.60	-3.20*	-2.20*	-0.28*	-0.02	0.44*
MS-4 × UHF-CAP-27	-3.44*	-3.15*	5.14*	2.05*	0.34*	0.35*	0.02
MS-4 × IIHR-37	-0.22	-1.49	3.37*	2.31*	-0.10	-0.44*	0.01
MS-6 × California Wonder	-3.96*	-5.93*	1.29	0.10	0.44*	0.18*	0.10
MS-6 × Solan Bharpur	-1.51	-0.82	5.52*	3.55*	0.35*	-0.14	-0.14
MS-6 × UHF- CAP-4	2.60*	2.73*	2.08	2.37*	0.07	0.10	-0.41*
MS-6 × UHF-CAP-27	1.82*	2.17	-12.68*	-6.76*	-0.62*	-0.46*	0.16
MS-6 × IIHR-37	1.04	1.85	3.79*	0.73	-0.25*	0.33*	0.28*
MS-7 × California Wonder	1.51	1.87	-1.03	-0.31	-0.04	-0.07	0.16
MS-7 × Solan Bharpur	-1.38	-1.36	-0.48	-1.18	-0.79*	-0.08	0.35*
MS-7 × UHF- CAP-4	-0.93	-1.13	1.12	-0.18	0.21	-0.07	-0.03
MS-7 × UHF-CAP-27	1.62	0.98	7.54*	4.71*	0.27*	0.11	-0.18
MS-7 × IIHR-37	-0.82	0.36	-7.16*	-3.04*	0.35*	0.11	-0.30*
S.E.(Sij)	0.88	1.29	1.02	0.81	0.10	0.08	0.09
S.E.	1.25	1.83	1.44	1.14	0.14	0.11	0.13
C.D._(0.05) (Sij)	1.80	2.65	2.09	1.65	0.21	0.16	0.19
C.D._(0.05) (Sij-Skj)	2.55	3.75	2.95	2.34	0.29	0.23	0.27

Estimates of GCA effects for parental genotypes for fruit diameter showed that the MS-7 lines were good general combiners, whereas the other two lines were poor combiners. Among the testers, IIHR-37 and UHF-CAP-27 were rated as good general combiners while, Solan Bharpur was the sole tester categorized as poor general combiner and the other two testers were considered average general combiners. Among fifteen cross combinations, MS-4 \times UHF-CAP-27, MS-6 \times IIHR-37, MS-4 \times Solan Bharpur and MS-6 \times California Wonder were good specific combiner for the character under study. Most of the crosses involved the parents with poor \times good, poor \times good, poor \times poor and poor \times average GCA effects for the fruit diameter. Hegde *et al.*, 2019 reported significant positive SCA effects in the cross California Wonder \times Arka Mohini (0.77) for fruit diameter in bell pepper.

For number of lobes, among male sterile lines, MS-4 was good general combiner, MS-6 was poor general combiner and MS-7 was average general combiner. Among the 5 testers used in the current research, UHF-CAP-27, IIHR-37 and UHF-CAP-4 were with good general combining ability for the character. Kaur *et al.*, 2018 also reported significant positive GCA effects in the parent UHF-14. The remaining two testers Solan Bharpur and California Wonder were grouped as poor and average general combiner, respectively. The estimation of specific combining ability effects for this character showed that five F₁ combinations namely, MS-6 \times IIHR-37 (poor \times good), MS-7 \times UHF-CAP-27 (average \times good), MS-4 \times UHF-CAP-27 (good \times good), MS-6 \times California Wonder (poor \times average) and MS-4 \times UHF-CAP-4 (good \times good) were good specific combiners. Kaur *et al.*, 2018 found AAC-16 \times California Wonder as a good specific combiner with SCA effects 0.15 for number of lobes per fruit.

For pericarp thickness, MS-6 was to be found as good general combiner. In contrast, MS-4 and MS-7 were observed as poor general combiners. California Wonder and UHF-CAP-4 among the testers were good general combiners. Solan Bharpur was the only tester classed as a poor general combiner and remaining testers were average general combiners. Kaur *et al.*, 2018 also reported positive GCA effects in the parent ACC-16 for this character. Among fifteen cross combinations, four combinations viz., MS-6 \times UHF-CAP-4, MS-4 \times Solan Bharpur, MS-6 \times IIHR-37 and MS-7 \times California Wonder were good specific combiners having parents with good \times good, poor \times poor, good \times average and average \times good GCA effects for pericarp thickness.

Table 6: Estimation of specific combining ability (SCA) effects of crosses for different characteristics in bell pepper

Cross(s) / Character	Average fruit weight (g)	Number of lobes per fruit	Pericarp thickness	Number of fruits per plant	Fruit yield per plant (g)	Harvest duration (days)
MS-4 × California Wonder	-3.13*	-0.04	-0.15*	-0.07	-32.88*	4.07*
MS-4 × Solan Bharpur	5.85*	0.05	0.25*	0.83*	101.35*	1.73
MS-4 × UHF- CAP-4	-4.24*	0.11*	-0.16*	-1.29*	-162.94*	-2.49*
MS-4 × UHF-CAP-27	6.32*	0.20*	0.09	-1.17*	-14.14	0.29
MS-4 × IIHR-37	-4.81*	-0.32*	-0.03	1.70*	108.62*	-3.60*
MS-6 × California Wonder	9.20*	0.15*	-0.10	-0.90*	37.72*	-2.40*
MS-6 × Solan Bharpur	-3.16*	-0.13*	-0.28*	0.80*	-21.12	-5.07*
MS-6 × UHF- CAP-4	8.57*	-0.07	0.30*	0.93*	197.76*	5.38*
MS-6 × UHF-CAP-27	-20.76*	-0.46*	-0.17*	-0.88*	-312.08*	0.49
MS-6 × IIHR-37	6.16*	0.51*	0.25*	0.05	97.72*	1.60
MS-7 × California Wonder	-6.07*	-0.12*	0.25*	0.97*	-4.83	-1.67
MS-7 × Solan Bharpur	-2.69*	0.08	0.03	-1.63*	-80.23*	3.33*
MS-7 × UHF- CAP-4	-4.33*	-0.05	-0.14*	0.36*	-34.81*	-2.89*
MS-7 × UHF-CAP-27	14.43*	0.26*	0.08	2.05*	326.22*	-0.78
MS-7 × IIHR-37	-1.34	-0.18*	-0.22*	-1.75*	-206.35*	2.00
S.E.(Sij)	1.05	0.05	0.07	0.16	12.33	0.99
S.E.	1.49	0.07	0.10	0.22	17.44	1.40
C.D. _(0.05) (Sij)	2.16	0.10	0.14	0.32	25.26	2.03
C.D. _(0.05) (Sij-Skj)	3.05	0.14	0.20	0.45	35.76	2.87

Kaur *et al.*, 2018 observed significant SCA effects in the cross UHF-11 \times California Wonder (0.29) for this character.

For number of fruits per plant, MS-4 and MS-6 showed good GCA effects. MS-7 was the only line with poor GCA effects. The testers, Solan Bharpur and UHF-CAP-4 were good general combiners for this character. However, remaining three testers were poor general combiners. These results are in accordance with Aditika (2018) who reported Solan Bharpur as good general combiner for number of fruits per plant. Seven cross combinations *viz.*, MS-7 \times UHF-CAP-27, MS-4 \times IIHR-37, MS-7 \times California Wonder, MS-6 \times UHF- CAP-4, MS-4 \times Solan Bharpur, MS-6 \times Solan Bharpur and MS-7 \times UHF- CAP-4 revealed noteworthy positive specific combining ability effects and these combinations shared parents with poor \times poor, good \times poor, poor \times poor, good \times good, good \times good, good \times good and poor \times good general combining effects. Hegde *et al.*, 2019 reported significant positive SCA effects in the cross Arka Mohini \times LC-10 (2.57) for this trait.

With respect to fruit yield per plant, the line MS-4 was the good general combiner, MS-7 was poor general combiner while, MS-6 line was found to be an average general combiner. Good general combining ability reported from testers UHF-CAP-4 and IIHR-37 while, others were found to be poor general combiners for fruit yield per plant. Rao *et al.* (2016) observed Arka Mohini and IIHR-4103 with significant GCA effects for fruit yield per plant. Significantly positive SCA estimates displayed by six F_1 combinations for fruit yield per plant classified these as good specific combinations, which were MS-7 \times UHF-CAP-27, MS-6 \times UHF- CAP-4, MS-4 \times IIHR-37, MS-4 \times Solan Bharpur, MS-6 \times IIHR-37 and MS-6 \times California Wonder. These cross combinations had parents with poor \times poor, average \times good, good \times good, good \times poor, average \times good and average \times poor GCA effects, correspondingly. Sarkar *et al.*, 2019 observed significant SCA effects in the cross BCC54 \times BCC24 (115.37) for fruit yield per plant.

All the male sterile lines were average general combiners for harvest duration. Among testers, UHF-CAP-27 was designated as a good general combiner for this character but IIHR-37 was identified as poor general combiner. The remaining testers were average combiners. Kaur *et al.*, 2018 observed significant GCA effects in the line UHF-6 for harvest duration. SCA analysis for harvest duration revealed three cross combinations *viz.*, MS-6 \times UHF- CAP-4, MS-4 \times California Wonder and MS-7 \times Solan Bharpur as good specific combiners involving parents with

average \times average GCA effects. Kaur *et al.*, 2018 reported positive SCA effects in the cross UHF-10 \times California Wonder (3.79) for harvest duration.

3.4 Estimates of genetic components of variance for different characteristics

Analysis of the data in Table 7 revealed that the estimates of σ^2 SCA were greater in magnitude than σ^2 GCA (average) in the F_1 generation for all the horticultural characteristics. Further, investigation of the additive (σ^2 g) and dominant (σ^2 s) component of variance supported the findings of the analysis of variance for combining abilities. The involvement of non-additive gene action has been discovered since SCA variances were higher than GCA values for all characters under consideration.

Table 7: Estimation of genetic components of variances for different characteristics

Character(s)	σ^2 GCA (Lines)	σ^2 GCA (Testers)	σ^2 GCA (Average)	σ^2 SCA	σ^2 g	σ^2 s	σ^2 g/ σ^2 s (Variance ratio)
Days to 50% flowering	7.09	16.41	2.03	7.53	4.06	7.53	0.54
Days to marketable maturity	11.28	18.39	2.53	10.23	5.05	10.23	0.49
Plant height	-4.94	-8.08	-1.11	48.46	-2.22	48.46	-0.05
Plant spread	-1.76	-2.32	-0.34	14.01	-0.69	14.01	-0.05
Number of primary branches	-0.01	-0.01	0.00	0.10	0.00	0.10	-0.03
Fruit length	0.06	0.36	0.04	0.26	0.07	0.26	0.28
Fruit diameter	0.01	0.06	0.01	0.09	0.01	0.09	0.14
Average fruit weight	-0.87	192.08	17.40	128.26	34.79	128.26	0.27
Number of lobes per fruit	-0.02	0.01	0.00	0.10	0.00	0.10	0.00
Pericarp thickness	-0.01	0.03	0.00	0.60	0.00	0.06	0.07
Number of fruits per plant	0.97	2.40	0.29	2.56	0.58	2.56	0.23
Fruit yield/ plant	-8277.44	3879.35	-274.41	44159.59	-548.82	44159.59	-0.01
Harvest duration	-2.58	-2.13	-0.39	15.11	-0.78	15.11	-0.05

Furthermore, for all the characteristics the variance ratio in F_1 was found less than one. Another time, it demonstrated the role of non-additive gene action in regulating almost all the characters in bell pepper under investigation. Non-additive gene action for fruit yield and yield contributing characteristics has also been recorded by Nascimento *et al.* (2004), Sood and Kaul (2006) and Kamble *et al.* (2009) and Kaur (2016) signifying that heterosis breeding will be an exclusive choice for their improvement in comparison to other breeding techniques.

4. CONCLUSION

According to the findings of the current investigation it has been concluded that among testers, Solan Bharpur for number of fruits per plant, UHF-CAP-4 for fruit yield per plant, California Wonder for earliness and ascorbic acid, UHF-CAP-27 for number of lobes per fruit and harvest duration and IIHR-37 for fruit length, diameter and average fruit weight can be developed as pre-breeding lines whereas, out of fifteen cross combinations, MS-4 \times UHF-CAP-27 and MS-7 \times UHF-CAP-27 were two best cross combinations on the basis of mean performance, specific combining ability and heterosis for majority of the horticultural characters. After multilocation testing, these combinations can therefore be used commercially for hybrid development.

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