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RESEARCH ARTICLE

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Heterosis and combining ability analysis for yield and its components in Indian mustard (*Brassica juncea* L. Czern & Coss)

Abstract Half diallel analysis of eight parents was carried out to identify the high heterotic crosses and their relationship in terms of general and specific combining ability (GCA & SCA) in *Brassica juncea* L. Czern and Coss at IARI, New Delhi, during 2007–2008 and 2008–2009. The relative heterosis and heterobeltiosis were observed to be the highest with respect to seed yield per 100 siliquae and days from sowing to 50% flowering in case of cross IC-199715 × IC-199714, EC-289602 × Prakash in the number of primary branches per plant and harvest index, Agra Local × Pusa Bahar in the length of main axis, Poorbijaya × Agra Local in the number of siliquae on main axis and EC-289602 × Pusa Bahar in the biologic yield per plant and seed yield per plant. Different cross combinations exhibited the maximum value of better and mid-parent heterosis for the remaining traits, viz., days to maturity, number of secondary branches per plant, plant height and 1000-seed weight. GCA and SCA variances were significant in all characters. The variance of GCA (σ^2g) was observed to be higher from sowing to 50% flowering and maturity in plant height and 1000-seed weight, whereas the variance of SCA (σ^2s) was higher in seed yield and other remaining parameters.

Keywords *Brassica juncea*, GCA, heterobeltiosis, Indian mustard, mid-parent heterosis, SCA

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1 Introduction

In recent years, substantial efforts were made to improve seed quality, seed yield and other yield-related parameters and/or to transfer its useful traits to related *Brassica* oil crops (Rakow, 1995; Meng et al. 1998; Singh, 2003; Singh et al., 1996). Breeding for heterosis is one of the most successful technological options being employed for the improvement of crop varieties. Heterosis is the interpretation of increased vigor, size, fruitfulness, development speed, resistance to disease and insect pests or climatic vigors, manifested by cross-bred organisms as compared with corresponding inbreds (Shull, 1952; Jinks and Jones, 1958). Development of hybrid cultivars has been successful in many *Brassica* spp. (Melchinger and Gumber, 1998; Becker and Robbelen, 1999; Miller, 1999).

Comprehensive analysis of the combining ability involved in the inheritance of quantitative characters and in the phenomenon of heterosis is necessary for the evaluation of various possible breeding procedures (Allard, 1960). Combining ability studies emphasized the preponderance effect of GCA on yield and most of the yield components, indicating the importance of additive gene action (Brandle and McVetty, 1989; McGee and Brown, 1995; Wos et al., 1999). On the other hand, Pandey et al. (1999) reviewed evidences for the presence of significant SCA effects for yield and yield components, indicating the importance of non-additive gene action. Singh et al. (2005) reported that non-additive genetic effects in addition to additive effects accounted for yield heterosis. It has been further suggested by Jinks (1955) that non-allelic interactions might be the cause of heterosis rather than special relations between genes at the same locus.

In Indian mustard (*Brasssica juncea*), Yadava et al., (1974) reported heterosis of 239 percent over the better parent for seed yield per plant. A wide range of positive heterosis for the number of primary and secondary branches per plant, plant height and seeds per siliqua was also reported (Rawat, 1975). In another study of partial diallel analysis of mustard, significant heterosis for yield per plant, the number of primary and secondary branches, the length of siliqua, 1000-seed weight and plant height was reported (Ram et al., 1976). Pradhan et al., (1993) reported 29 to 92% heterosis over the best-yielding parents in *B. juncea* by crossing the parents of Indian and exotic origin. Banga and Labana (1984) reported up to 200% heterosis in *B. juncea*. It was further confirmed that some of the crosses exhibited heterobeltiosis also. Khulbe et al. (1998) and Verma et al. (2000) reported a significant degree of heterobeltiosis in several varieties of Indian mustard. Therefore, this study has the following objectives: (1) to estimate the relative importance of GCA and SCA variances and (2) to determine the level of mid- and high-parent heterosis for yield and its components.

2 Materials and methods

2.1 Plant materials

Eight genetically diverse lines, viz., EC-289602, Poorbijaya, IC-199715, Agra Local, Prakash, RH-30, IC-199714 and Pusa Bahar, were collected from the seed stocks of Division of Genetics and Seed Production Unit of Indian Agriculture Research Institute, New Delhi, India. The parental lines were chosen in a systematic random way to represent the phenotypic diversity, and a study was conducted for yield and yield-related parameters.

2.2 Field experiment

During the rabi season of the years 2007–2008 and 2008–2009, all eight parents were crossed in a half-diallel mating design following method IV of Griffing (1956) at IARI, New Delhi, located at an altitude of 228.16 m, 77°10′E latitude and 28°40′N longitude. The annual precipitation rate is around 710 mm, and soil is sandy loam. The parents were sown in Randomized Block Design (RBD) with three replications. Each plot consisted of a single row of 5-m length. The distance between rows and plants was kept at 45 cm and 15 cm, respectively. The recommended doses of nutrients, i.e. 80 kg $N \cdot hm^{-2}$, 60 kg $P_2O_5 \cdot hm^{-2}$ and 40 kg $K_2O \cdot hm^{-2}$, were applied. Half of N and the entire P_2O_5 and K_2O were applied at the time of field preparation as the basal dose. The remaining quantity of nitrogen was given as the top dressing. Other operations were undertaken to keep the field free from weeds.

2.3 Data collection and analysis

Observations were recorded for developmental, quantitative and qualitative characters on a single plant basis. Phenotypic traits were recorded in days from sowing until about mid-flowering and 90% maturity, including the number of primary branches (NP) per plant (productive branches originating from the main stem); the number of secondary branches (NS) per plant (productive branches developed from the primary branches); the length of the main axis (LM) measured in centimeters from the base of the terminal primary branch to the tip of the main axis; the plant height (PH) measured in centimeters from the base of the plant to the apex of the main axis; the number of siliquae on the main axis (SM) counted at the time of maturity for each sampled plant (SP); the seed yield from 100 siliquae (seeds from the 100-siliquae of five sampled plants were weighed); the biologic yield per plant (BP) (average weight of five sampled plants, seed yield per plant (SP), harvest index (HI), 1000-seed weight and weight recorded in grams by METLER electronic balance).

The data collected were subjected to analysis of variance according to Fisher and Yates (1967). Combining ability analysis was performed using IRRISTAT software (IRRI.org, IRRI, Manila, Philippines) following Method IV of Griffing (1956). The computation of heterosis values was carried out according to the method of Turner (1953) and Hayes et al. (1955). The average F_1 value was used for estimation of heterosis expressed in percentage over mid parent (MP) and better parent (BP) values, where MP value = $(P_1+P_2)/2$, Relative heterosis = $[(F_1\text{-MP})/\text{MP}] \times 100$, heterobeltiosis = $[(F_1 - \text{BP})/\text{BP}] \times 100$.

3 Results

3.1 Estimation of combining ability

Results from the partitioning of the sum of squares of the F_1s (the numerous progenies received in F_1 generation) into GCA and SCA are presented in Table 1. It was observed that mean squares of both GCA and SCA were significant ($P \leqslant 0.01$) for all characters. Magnitude of σ^2g (variance of GCA) was higher than that of σ^2s (variance of SCA) for characters, viz., days to 50% flowering (DF), days to maturity (DM), plant height and 1000-seed weight, indicating a predominance of additive gene action. On the other hand, the estimates of σ^2s were higher than those of σ^2g with respect to the number of primary and secondary branches per plant, the length of the main axis, the number of siliqua on the main axis (SM), the seed yield per 100 siliqua (SS), the biologic yield per plant, the seed yield per plant and the harvest index (Table 2), which indicated the preponderance of non–additive gene action.

For *Brassica*, early flowering and maturity reduced plant height and length of main axis are desirable traits, and hence, the higher the negative values of GCA and SCA, the better the genotypes for breeding. In our study, the maximum negative GCA value was exhibited by the genotype EC-289602 (Table 3) for days to 50% flowering (–3.08), plant height (–15.75), and the length of the main

Table 1 ANOVA for combining ability of 12 characters in 8 × 8 half-diallel set of *Brassica juncea* (L.) Czern and Coss

sources	Df	DF	DM	NP	NS	LM /cm	PH /cm	SM	SS	BP	SP	HI /%	SW
GCA	7	461.68**	1506.8**	10.51**	119.63**	55.52**	5607.94**	304.22**	18.88**	5535.03**	206.26**	78.11**	9.01**
SCA	28	13.52**	23.59**	1.42**	19.45**	79.59**	142.03**	56.27**	2.74**	4617.61**	290.63**	11.76**	0.27**
error	70	1.8	0.7	0.06	2.99	4.35	12.74	3.36	0.35	60.44	3.44	1.3	0.02

Note: * and ** mean significance at 5% and 1% level, respectively.

Table 2 Estimates of σ^2g, σ^2s, σ^2e and σ^2g/σ^2s for 12 characters in 8 × 8 half-diallel set of *Brassica juncea* (L.) Czern and Coss

sources	DF	DM	NP	NS	LM	PH	SM	SS	BP	SP	HI	SW
σ^2g	19.17	62.75	0.44	4.86	2.13	233.13	12.54	0.77	228.11	8.45	3.21	0.37
σ^2s	11.94	22.89	1.36	16.46	75.24	129.29	52.91	2.39	4557.17	287.19	10.73	0.25
σ^2e	1.58	0.70	0.06	2.99	4.35	12.74	3.36	0.35	60.44	3.44	1.03	0.02
σ^2g/σ^2s	1.61	2.74	0.32	0.30	0.03	1.80	0.24	0.32	0.05	0.03	0.30	1.48

axis (−1.21), but positive GCA values were observed for the number of secondary branches per plant (4.50) and seed yield per 100 siliquae (0.93). Further, the genotype Prakash exhibited positive GCA in the number of siliqua on the main axis (2.75), biologic yield (28.99) and seed yield per plant (6.88), with Pusa Bahar (−6.65) followed by EC-289602 (−6.37) exhibiting positive GCA for days to maturity, and Agra Local (−0.32) followed by EC-289602 (0.21) exhibiting positive GCA in the number of primary branches per plant. The genotypes IC-199715 (1.76) and IC-199714 (0.82) displayed a maximum positive GCA effect with respect to harvest index and 1000-seed weight, respectively (Table 3).

Similarly, the maximum negative SCA effect was exhibited by EC-289602 × Prakash (−3.64) for days to 50% flowering, EC-289602 × Poorbijaya (−5.74) for days to maturity, Poorbijaya × IC-199714 (−14.30) in plant height, IC-199715 × Prakash (−13.02) in length of the main axis. The highest positive SCA value was observed in the cross combinations of EC-289602 × Agra Local in the number of primary (2.42) and secondary branches per plant (11.05), Poorbijaya × IC-199715 (10.39) in the number of siliqua on the main axis, RH-30 × Pusa Bahar (1.74) in the seed yield per 100 siliquae, EC-289602 × Pusa Bahar (73.57) in the biologic yield per plant, IC-199715 × Agra Local in the seed yield per plant (21.25) and the harvest index (4.27) and Poorbijaya × Agra Local (1.26) in 1000-seed weight (Table 4).

3.2 Estimation of relative heterosis and heterobeltiosis

The estimates of heterosis that increased or decreased over better and mid-parental values for all the studied characters in half-diallel analysis are presented in Table 5. The results

Table 3 Estimates of GCA effects of parental lines for 12 characters in 8 × 8 half-diallel set of *Brassica juncea* (L.) Czern and Coss

genotypes	DF	DM	NP	NS	LM	PH	SM	SS	BP	SP	HI	SW
EC-289602	−3.08**	−6.37**	0.21**	4.50**	−1.21**	−15.75**	−2.89**	0.93**	−8.62**	−3.96**	−0.91**	−1.16**
Poorbijaya	−1.11**	−4.78**	−0.10*	−0.40	−0.68	−4.09**	−0.82	0.74**	−10.99*	−1.60*	−0.68	0.03
IC-199715	−1.09**	4.73**	−0.34**	−0.91**	2.42**	4.54**	−0.39	0.09	−7.93**	3.02**	1.76**	0.61**
Agra Local	−1.93**	−1.62**	0.32**	1.27**	−0.35	−14.98**	−1.32**	−0.91**	9.64**	−3.01**	−2.07**	0.55**
Prakash	2.03**	7.49**	0.14**	2.12**	2.92**	6.30**	2.75**	0.73**	28.99**	6.88**	1.61**	0.35**
RH-30	2.74**	5.85**	−0.14**	−0.95**	1.47**	4.36**	−0.21	0.40**	13.18**	3.77**	−0.05	0.23**
IC − 199714	−0.63	2.78**	−0.61**	−1.87**	0.15	3.29**	−0.65	−1.74**	−1.44	2.56**	0.85**	0.82**
Pusa Bahar	−2.10**	−6.65**	−0.83**	−2.95**	2.66	−4.74**	0.37	0.71**	−12.22**	−1.03	1.64**	0.43**
SE(gi)+	0.25	0.16	0.04	0.33	0.40	0.69	0.35	0.11	1.51	0.36	0.19	0.03
CD 5%	0.49	0.31	0.08	0.65	0.78	1.35	0.69	0.22	2.96	0.71	0.37	0.06
CD 1%	0.65	0.41	0.10	0.85	1.03	1.77	0.90	0.28	3.90	0.93	0.49	0.08
SE (gi − gj)+	0.36	0.24	−0.07	0.49	0.60	1.03	0.52	0.17	2.24	0.53	0.29	0.04
CD 5%	0.71	0.47	−0.14	0.96	1.18	2.02	1.02	0.33	4.39	1.04	0.57	0.08
CD 1%	0.93	0.62	−0.18	1.26	1.55	2.66	1.34	0.44	5.78	1.36	0.75	0.10

Table 4 Estimates of SCA effects of parental lines for 12 characters in 8×8 half-diallel set of *Brassica juncea* (L.) Czern and Coss

crosses	DF	DM	NP	NS	LM	PH	SM	SS	BP	SP	HI	SW
EC-289602×Poorbijaya	1.49	−5.74**	−0.23	0.62	−2.35	−1.87	−0.28	−1.16**	16.53**	1.11	−0.08	−0.28**
EC-289602×IC-199715	−3.61**	2.48**	−0.13	−1.27	13.96**	−1.99	0.93	1.33**	4.44	0.86	0.11	−0.35**
EC-289602×Agra Local	−1.78**	1.33*	2.42**	11.05**	2.35	0.65	2.03	−0.47	58.54**	12.72**	0.51	0.05
EC-289602×Prakash	−3.64**	11.55**	1.63**	6.13**	−1.03	7.94**	−5.71**	−1.62**	−4.17	8.50**	4.08**	0.10
EC-289602×RH-30	−2.87**	−0.14	0.66**	−1.06	−3.87**	−1.40	4.75**	1.52**	40.17**	13.11**	2.59**	−0.34**
EC-289602×IC-199714	1.89*	−3.41**	0.28	−0.31	0.93	6.57**	1.86	−0.19	−18.04**	−1.52	0.19	0.01
EC-289602×Pusa Bahar	1.96*	−1.48**	0.69**	1.77	−5.61**	−7.20**	−4.72**	0.73	73.57**	12.23**	−1.24	−0.13
Poorbijaya×IC-199715	−2.09*	4.00**	0.41	−0.97	3.25*	−2.74	10.39**	−1.34**	−2.50	1.64	0.60	−0.24**
Poorbijaya×Agra Local	1.74*	−3.66**	0.59**	1.52	0.93	−2.45	3.82**	−0.97*	10.60*	−13.17**	−4.97**	1.26**
Poorbijaya×Prakash	−0.62	−0.44	0.59*	−1.40	0.39	−1.99**	−1.42**	−0.28	−23.22	16.44	2.00	0.11
Poorbijaya×RH-30	−1.19	3.04**	−0.13	0.58	1.26	0.48	3.37**	1.67**	−6.28	2.89*	2.12**	−0.14
Poorbijaya×IC-199714	−1.43	−0.89	−0.58**	0.42	−11.21**	−14.30**	−0.02	1.65**	−25.65**	−5.74*	0.21	−0.63**
Poorbijaya×Pusa Bahar	1.47	2.20	−0.42	0.48	−0.72	1.67	−0.73	−1.04**	9.12	4.60	0.35	−0.09
IC-199715×Agra Local	−0.03	−1.10*	0.17	1.13	−0.45	−9.20**	2.53*	0.19	36.85**	21.25**	4.27**	−0.26**
IC-199715×Prakash	0.95	1.95**	−0.23	−2.12	−13.02**	−2.36	1.79	−0.13	−36.86**	−15.14**	−2.16**	−0.27**
IC-199715×RH-30	1.54	−0.07	−0.20	−0.81	1.71	0.04	5.91**	−0.16	5.36	−1.70	−0.57	0.28**
IC-199715×IC-199714	−1.19	2.83**	0.02	0.77	−0.22	−4.59*	−1.47	1.63**	−29.24**	−5.99**	1.85**	−0.13
IC-199715×Pusa Bahar	0.88	3.91**	−0.84**	−2.48**	6.57**	0.82	−0.89	0.08	15.71**	2.76*	−0.31	0.17
Agra Local×Prakash	−1.55	−1.20*	−0.65**	−2.30*	1.36	−10.90**	3.55**	1.58**	−29.26**	−5.45**	−0.26	−0.32**
Agra Local×RH-30	−0.46	−3.73**	0.88**	1.84	6.79**	3.17	−2.49*	−0.45	7.40	3.16**	0.72	−0.22*
Agra Local×IC-199714	0.81	−3.49**	−0.48**	−4.24**	−11.33**	−3.50	−4.21**	−0.83*	33.19*	−5.63**	−4.43**	0.90**
Agra Local×Pusa Bahar	2.21**	1.11*	−1.17**	−3.33**	5.71**	9.69**	2.04	0.92*	−24.53**	−2.71*	0.81	−0.23*
Prakash×RH-30	0.52	1.0	0.98**	0.76	0.72	8.59**	−12.56**	−0.94*	−41.81**	−10.89**	−0.03	0.30**
Prakash×IC-199714	−3.05**	0.40	0.80**	−2.83*	3.27*	−9.04**	−1.61	−1.81**	−7.85	−2.18	−0.43	0.23*
Prakash×Pusa Bahar	−0.02	−2.50	0.58	−1.01	−4.18*	−2.79	3.36	−0.23*	−20.24	−10.10*	2.51	−0.35**
RH-30×IC-199714	−0.12	0.54	0.06	−0.52	5.11**	−0.66	6.84**	−0.01	62.82**	17.76**	0.77	0.26**
RH-30×Pusa Bahar	0.28	−3.70**	0.37*	2.06	−3.27*	−2.14	4.26**	1.74**	67.43**	15.34**	−1.09	0.05
IC-199714×Pusa Bahar	1.21	−0.63	0.17	0.19	0.14	−0.43	−0.46	−1.80**	27.22**	15.39**	3.51**	−0.12
SE sij	0.82	0.54	0.16	1.12	1.35	2.32	1.19	0.38	5.06	1.20	0.66	0.09
CD 5%	1.61	1.06	0.31	2.20	2.65	4.55	2.33	0.74	9.92	2.35	1.29	0.18
CD 1%	2.12	1.39	0.41	2.89	3.48	5.99	3.07	0.98	13.05	3.10	1.70	0.23

Note: * and ** mean significance at 5% and 1% level, respectively.

Table 5 Estimates of heterosis for 12 characters in 8×8 half-diallel set of *Brassica juncea* L. Czern & Coss

crosses	heterosis/%	DF	DM	NP	NS	LM	PH	SM	SS	BP	SP	HI	SW
EC-289602×Poorbijaya	BP	−2.79	18.55**	−6.98**	−3.16	−20.24**	−16.70**	−4.58	−22.00**	81.31**	60.63**	−6.87**	53.64**
	MP	−7.69**	2.98*	2.56**	15.00*	−9.77**	−5.08	−2.34	−22.00**	107.34**	122.41**	10.31**	−33.33**
EC-289602×IC-199715	BP	1.68	18.55**	6.22*	−7.37**	14.62**	−17.21**	−16.46**	−4.00**	22.10*	14.86**	−6.00**	−50.96**
	MP	−4.71**	4.87**	19.4**	13.55**	13.43**	−1.1	−7.12**	7.87**	35.65**	58.27**	20.22**	−23.00**
EC-289602×Agra Local	BP	3.41*	9.86*	22.22**	12.63**	−3.75	−8.91	5.34	−20.00**	1.5	30.70**	28.63**	−30.56**
	MP	2.54	3.13**	37.50**	35.44**	6.29**	−2.47	8.66**	6.98**	13.45	54.40**	37.40**	−0.66**
EC-289602×Prakash	BP	−3.35*	4.64*	38.46**	−3.16	−13.92**	−7.07	−14.58**	−6.00**	−15.88	16.34**	37.66**	−25.00**
	MP	8.95**	10.19**	45.95**	21.05**	−4.3	4.33	−10.55**	6.09**	9.39	67.22**	59.81**	4.90**
EC-289602×RH-30	BP	3.91*	16.52**	−6.38**	−22.11**	−14.91**	−11.95**	−30.62**	−4.00**	63.79**	38.51**	−15.31**	−49.56**
	MP	−2.62	1.9	7.32**	−8.07**	−5.00*	−0.26	−23.71**	9.09**	82.45**	85.83**	5.53**	−26.92**
EC-289602×IC-199714	BP	−9.50**	10.75**	11.11**	−17.81**	2.64	−14.15**	−11.11**	−16.00**	−11.47	−31.91**	−23.17**	−15.29**
	MP	−14.29**	−0.13	12.68**	0.65	9.07**	−2.62	2.89	−1.18	6.76	−12.73**	−5.37**	−20.56**
EC-289602×Pusa Bahar	BP	13.25**	4.64**	25.71**	−6.32**	11.99**	−12.67**	17.56**	2.00**	95.43**	137.95**	−22.18**	−44.12**
	MP	8.99**	2.41*	33.33**	27.14**	12.63**	−3.54	−6.09*	12.09**	142.27**	142.58**	−4.92**	−15.07**
Poorbijaya×IC-199715	BP	−1.52	3.91**	11.63**	4.62	0.47	−11.14**	9.76**	−10.00**	−16.41	−9.43**	−9.73**	−19.11**
	MP	−2.74	2.15	20.0**	8.80**	1.14	−6.1	24.57**	1.12	−13.63	−14.02**	−0.76	−4.87**
Poorbijaya×Agra Local	BP	9.09**	4.62**	−4.44**	4.62	−13.86**	−9.11*	36.80**	−10.00**	11.41	−9.15**	−18.63**	41.82**
	MP	2.67	−2.86*	−2.27**	6.25**	−11.51**	−2.79	37.20**	4.65**	14.35	4.12	−9.04**	43.12**
Poorbijaya×Prakash	BP	−0.51	0.44	−2.33**	−16.92**	−11.51**	15.41**	−1.39	−16.00**	−16.39	10.89**	25.80**	−8.18**
	MP	−1.25	0.44	2.44**	−11.48**	−9.76**	17.38**	5.58*	−13.40**	−2.28	26.20**	28.85**	−3.81**
Poorbijaya×RH-30	BP	1.52	1.35	−14.49**	7.58**	−10.26**	0.6	−11.88**	6.00**	35.66**	34.16**	−6.96**	−6.19**
	MP	−2.74	0.67	−11.11**	8.40**	−8.82**	1.29	−1.05	20.45**	39.75**	37.58**	−1.46	−4.93**
Poorbijaya×IC-199714	BP	−5.05**	2.14	−11.63**	4.64	−34.48**	−15.65**	−20.11**	−6.00**	12.13	26.80**	2.21	−36.84**
	MP	−5.29**	−1.38	−3.80**	8.80**	−29.95**	−15.20**	−6.89**	10.59**	22.33**	31.97**	7.49**	−23.12**
Poorbijaya×Pusa Bahar	BP	13.86**	15.28**	−16.28**	−18.46**	11.18**	6.47	16.80**	−26.00**	19.97	40.52**	8.62**	−20.69**
	MP	3.85**	2.47*	−2.70**	−3.64	26.39**	−3.17	30.36**	−18.68**	64.42**	87.77**	12.84**	−12.20**
IC-199715×Agra Local	BP	−3.41*	4.87**	−4.44**	14.29**	−24.51**	−23−57**	−19.51**	7.69**	32.18**	45.75**	8.74**	−17.83**
	MP	−10.29**	−0.85	4.88**	17.07**	−21.95**	13.96**	−8.01**	12.00**	33.08**	76.45**	32.12**	−2.64**
IC-199715×Prakash	BP	−4.98**	2.76*	7.69**	0	−22.20**	−15.88**	0	−17.02**	27.66*	−14.84**	−8.25**	−24.20**
	MP	−5.45**	1.02	10.53**	2.56	−20.14**	−9.68*	6.49*	−9.30**	−13.48	−8.74**	3.09*	−7.39**
IC-199715×RH-30	BP	−6.90**	0	−31.91**	−19.70**	−6.81**	−10.23**	−15.85**	15.38**	38.18**	46.84**	5.75**	−12.10**
	MP	−6.90**	−1.02	−23.81**	−15.87**	−4.70*	−4.53	−14.81**	16.83**	38.60**	52.98**	10.01**	2.22**

(*Continued*)

crosses	heterosis/%	DF	DM	NP	NS	LM	PH	SM	SS	BP	SP	HI	SW
IC – 199715×IC-199714	BP	–15.58**	3.57**	13.51**	23.33**	–12.30**	–16.04**	–23.33**	23.08**	31.25**	29.71**	–1.00	–9.92**
	MP	–16.42**	1.75	–15.01**	23.33**	–5.65*	–10.83**	–19.77**	29.73**	38.87**	43.6**	3.87**	–6.10**
IC-199715×Pusa Bahar	BP	6.62**	7.50**	–21.62**	–15.00**	–9.47**	–12.23**	–18.90**	14.63**	8.38	8.57**	0.5	–9.55**
	MP	–4.07**	–2.64*	–14.71**	–2.86	3.52	–4.18	1.14	17.50**	45.40**	51.40**	6.63**	–3.07**
Agra Local×Prakash	BP	–1.14	7.18**	2.22**	6.35**	–2.69	–11.79**	–12.50**	–6.38**	–7.17	13.37**	21.47**	7.41**
	MP	–7.69**	–0.48	4.76**	11.67**	–1.96	–7.15	–5.62*	6.02**	10.42	44.94**	32.87**	11.54**
Agra Local×RH-30	BP	5.68**	3.85**	2.13**	4.55	–0.45	–5.53	–23.12**	18.42**	34.70**	36.02**	0.27	21.24**
	MP	–1.85	–2.88*	4.33**	6.98**	0.68	0.4	–13.07**	21.62**	34.19**	59.27**	17.93**	23.98**
Agra Local×IC-199714	BP	0	1.79	8.89**	0	–29.13**	–14.29**	–44.44**	–16.67**	17.44	–5.67*	–29.52**	5.26**
	MP	–6.13**	–1.98	20.99**	2.44	–26.15**	–8.78*	–33.99**	–15.49v	25.06**	4.31*	–17.71**	29.03**
Agra Local×Pusa Bahar	BP	7.23**	6.11**	–20.00**	–9.52**	19.81**	–5.83	21.95**	–7.32**	–10.68	13.16**	–7.91**	–1.47**
	MP	4.09**	1.87	–5.26**	5.56**	32.98**	–2.6	35.14**	–1.30**	20.36**	35.79**	6.45**	9.84**
Prakash×RH-30	BP	1.48	0.9	8.51**	0	–23.63**	–6.86	–36.25**	–10.64**	9.43	9.90**	2.14	–2.65**
	MP	1.98	0.22	18.60**	7.32**	–23.34**	–5.9	–32.89**	–1.18	8.07	22.31**	10.72**	3.29**
Prakash×IC-199714	BP	–1.51	3.57**	–20.51**	–15.00**	–1.5	–7.92	–27.22**	–36.17**	–47.13**	–41.58**	–5.24**	–9.30**
	MP	–2	0	–17.33**	–12.82**	3.38	–6.84	–19.14**	–26.83**	–33.85**	–31.20**	1.85	1.85**
Prakash×Pusa Bahar	BP	15.00**	10.56**	–23.08**	–12.28**	4.79	–10.91*	–11.11**	–10.64**	–57.07**	–42.57**	17.47**	–22.79**
	MP	4.09**	–1.73	–14.29**	–1.96	17.09**	–9.27*	5.35*	4.55**	3.44**	–16.55**	24.77**	–11.02**
RH-30×IC-199714	BP	–3.52*	2.62	–34.84**	–36.36**	2.04	–1.71	–6.67*	7.89**	1.52	2.48	0	–6.43
	MP	–4.48**	–0.23	–25.30**	33.33**	7.46**	–1.06	–1.18	12.33**	7.72	9.27**	0.89	12.68**
RH-30×Pusa Bahar	BP	20.48**	8.33**	–12.77**	–18.18**	–1.49	–0.38	–7.50*	14.63**	–13.48	–17.39**	–5.28**	–19.84**
	MP	8.40**	–2.99**	5.13**	–2.7	10.44**	2.45	14.29**	18.99**	16.29	12.24**	–3.32**	–12.45**
IC-199714×Pusa Bahar	BP	–0.6	8.61**	–13.89**	–10.0**	–3.36	–17.60**	–43.33**	14.63**	26.88*	70.21**	34.07**	–37.43**
	MP	–9.59**	0.26	–7.46**	2.86	3.24	–15.14**	–26.88**	–7.88**	63.58**	121.20**	35.66**	–3.29**
S E d	BP	1.63	1.38	0.34	2.44	2.6	4.55	3.3	0.71	10.97	2.49	1.56	0.19
	MP	1.46	1.13	0.29	2.11	2.38	4.12	2.63	0.66	9.5	2.2	1.31	0.17
CD 5%	BP	3.19	2.7	0.67	4.78	5.1	8.92*	6.47	1.39	21.5	4.88	3.06	0.37
	MP	2.86	2.21	0.57	4.14	4.66	8.08	5.15	1.29	18.62	4.31	2.57	0.33
CD 1%	BP	4.19	3.55	0.87	6.27	6.68	11.69	8.48	1.82	28.19	6.4	4.01	0.49
	MP	3.75	2.9	0.75	5.42	6.12	10.59	6.76	1.7	24.42	5.65	3.37	0.44

Note: * and ** mean significance at 5% and 1% level, respectively.

revealed that, of the 28 crosses, the equal number of genotypes showed a positive and negative heterobeltiosis during sowing to 50% flowering with the highest value observed in IC-199715 × IC-199714 (−15.58%), while 19 genotypes displayed a negative relative heterosis, of which IC-199715 × IC-199714 showed the maximum (−16.42%) relative heterosis. Moreover, all of the 28 genotypes had positive heterobeltiosis during sowing to maturity and the best performance in the cross IC-199715 × RH-30, whereas 16 crosses had positive mid-parent heterosis and 12 crosses had negative heterosis with the maximum heterosis of −2.99% in RH-30 × Pusa Bahar. Further, for the number of primary branches per plant, 11 genotypes showed positive heterobeltiosis with the highest value of 38.46% in EC-289602 × Prakash, and 16 genotypes showed positive relative heterosis with the highest value of 45.95% in EC-289602 × Prakash. Lastly, 12 genotypes were found to have a positive better parent heterosis for the number of secondary branches per plant with the highest value of 23.33% in IC-199715 × IC-199714, whereas 20 genotypes were found to be associated with positive mid-parent heterosis with the highest value of 35.44% in EC-289602 × Agra Local.

Correspondingly, in case of the length of the main axis, the positive better parent heterosis among eight crosses showed the highest value of 19.81% in Agra Local × Pusa Bahar, and the mid-parent heterosis among 14 crosses showed the highest value of 32.98% in Agra Local × Pusa Bahar. Moreover, 20 five genotypes, of which IC-199715 × Agra Local had the highest value of 23.57%, exhibited negative heterobeltiosis for plant height, and 20 two crosses exhibited negative relative heterosis and highest (−15.20%) in Poorbijaya X IC-199714; for the number of siliquae on main axis, seven crosses displayed a positive better parent heterosis with the highest value of 36.80% in Poorbijaya × Agra Local, and 11 crosses displayed a positive mid-parent heterosis with a maximum heterosis of 37.20% in the cross combination of Poorbijaya × Agra Local. Further, ten out of 28, of which IC-199715 × IC-199714 had the highest value of 23.08% and 18 out of 28 genotypes of which IC-199715 × IC-199714 had the highest value of 29.73%, were found to have the positive better and mid-parent heterosis, respectively, in seed yield per 100 siliquae. Moreover, in case of the biologic yield per plant, the highest value of 95.43% heterobeltiosis was observed in EC-289602 × Pusa Bahar among 19 positive crosses found, while the maximum of 142.27% relative heterosis of EC-289602 × Pusa Bahar was recorded among the 24 positive crosses observed. For the trait seed yield per plant, the maximum heterobeltiosis in EC-289602 × Pusa Bahar and the relative heterosis in EC-289602 × Pusa Bahar were found to be 137.95% and 142.58%, respectively. Out of 28 genotypes, 23 were observed to have positive better parental (BP) and mid-parental (MP) heterosis. Moreover, the equal number of genotypes exhibited the positive and negative better parent heterosis with the maximum of 37.66% in EC-289602 × Prakash, and 21 genotypes exhibited the positive mid-parent heterosis in the harvest index, with the maximum of 59.81% in EC-289602 × Prakash. As for the 1000-seed weight, five crosses displayed the positive heterobeltiosis with the maximum of 53.64% in Poorbijaya × Agra Local, and ten crosses were found to possess the positive relative heterosis with the maximum heterosis of 43.12% in cross combination of EC-289602 × Poorbijaya.

4 Discussion

The characters like early maturity, flowering, reduced plant height and length of main axis are preferred in *Brassica* group, which enable plant breeders to produce varieties evading or tolerating the abiotic stresses like heat and lodging, as well as possess accurate seed formation due to the large seed filling period. They also provide ample time for the cultivation of the succeeding crop. Therefore, the negative combining ability effect and heterosis are desirable for these traits. Remaining yield-related characters, such as the number of primary and secondary branches per plant, seed yield per 100 siliquae, seed yield per plant, biologic yield per plant and harvest index, provide more opportunities for increasing yield, and hence, the positive combining ability effect and positive heterosis are preferred. Therefore, estimation of heterosis over mid-parent (relative heterosis) may be useful in identifying true heterotic cross combinations. Since higher yields in F_1 may be due to fixable (additive) and/or non-fixable (non-additive) gene action, the total effect partition of F_1 progeny into general and specific combining ability effects deciphers the causes of heterosis.

In our study, the variance of SCA exhibited a higher value than the variance of GCA in traits like the number of primary and secondary branches per plant, the length of the main axis, the number of siliquae on the main axis, seed yield per 100 siliquae, the biologic and seed yield per plant and the harvest index. This observation depicts the preponderance of non-additive gene action for these traits. Hence, these traits can be exploited through heterosis breeding for enhancing the yield of Indian mustard. These findings are in accord with the results of Brandle and McVetty, (1989) and Teklewold and Becker (2005).

Likewise, the GCA value was higher than the SCA value during days from sowing to maturity (−6.37) and in plant height (−15.75). These results are further corroborated with the findings of Teklewold et al. (2005) and Nassimi et al. (2006). The SCA effect was predominantly significant in seed yield and other yield-related characters. The SCA value in seed yield per plant (21.25), the number of secondary branches per plant (11.05), the number of siliquae on the main axis (10.39) and the harvest index (4.27) are very much in accordance with the earlier reports (Teklewold et al., 2005; Nassimi et al., 2006; Wang et al., 2007; Satwinder et al., 2000). These observations imply a fact that selected genotypes hold great promise for the development of hybrid varieties, as the heterosis exploits the non-additive component of combining ability.

In our heterosis analysis, the relative heterosis of 142.58% with respect to seed yield per plant is similar to the reported values (Singh et al., 1996; Mahto et al., 2004; Turi et al., 2006). The relative heterosis of 45.95% in the number of primary branches per plant is much higher than the findings of Mahmood et al. (2003) but is confirmed with the reports of Singh et al. (1985), Varshnay (1985) and Ali et al. (2000). Heterobeltiosis in plant height is −23.58%, which is in compliance with earlier findings (Khulbe et al., 1998; Verma et al., 2000; Weirong et al., 1999). Similarly, in the number of siliquae on the main axis, the mid-parent heterosis (37.20%) is higher than the observation of Mahto et al. (2004) but lower than that of Mahmood et al. (2003). Moreover, the relative heterosis during days from sowing to maturity and to 50% flowering was −2.99% and −16.42%, respectively, which is in accordance with the previous reports (Singh et al., 2005; Mahto et al. 2004; Thakur and Sagwal, 1997).

The heterotic and combining ability analysis revealed that the genotype EC-289602 had significantly desirable GCA values in seven characters and was associated with four crosses that exhibited the highest SCA value. Similarly, in mid or better parent heterosis, EC-289602 is involved in crosses that displayed the maximum value of one or the other type of heterosis in six characters. The genotype IC-199715 is also a promising genotype involved in four crosses with the highest SCA value as well as in crosses that exhibit the maximum heterotic value in five characters.

Henceforth, the two genotypes EC-289602 and IC-199715 can be used as potential parents for combining desirable characters like early maturity as well as enhancing the seed yield through heterosis breeding in future crop improvement programmes.

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