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Estimation of Standard Heterosis in Indian Mustard [*Brassica juncea* (L.) Czern. & Coss.]

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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

The present study evaluated standard heterosis for seed yield and 15 associated traits in 40 cross combinations of Indian mustard [*Brassica juncea* (L.) Czern. & Coss.]. Crosses developed during *Rabi* 2025 were evaluated during *Rabi* 2026 at the Experimental Farm, Zonal Agricultural Research Station, Morena, Madhya Pradesh, India, in a randomized block design with three replications. The zonal check Maya and national check Kranti were used for comparison. Considerable variation in standard heterosis was observed across the 16 traits. For seed yield per plant, standard heterosis ranged from −55.62% to 54.07% over Maya and from −59.46% to 40.75% over Kranti. Vasundhara × PM-26 recorded the highest positive standard heterosis for seed

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yield per plant over both Maya (54.07%) and Kranti (40.75%). Pusa Bold × Pusa Vijay, Varuna × NPJ-253, Varuna × PM-28, Kranti × NPJ-253, Rohini × PM-28, Maya × Pusa Vijay and Pusa Bold × PM-28 also expressed significant positive heterosis over both checks. Different cross combinations showed desirable heterosis for earliness, reduced plant height, branching, siliquae number, seeds per siliquae, siliquae length, test weight, biological yield and harvest index. The results identify promising hybrid combinations for heterosis-based improvement of Indian mustard. Their performance should be confirmed through multi-location and multi-season evaluation before their use in further breeding or cultivar-development programmes.

Keywords: *Brassica juncea; Indian mustard; standard heterosis; seed yield; yield-attributing traits; hybridization; cross combinations; zonal check; national check; genetic improvement*

1. Introduction

Indian mustard [*Brassica juncea* (L.)] is one of the most economically and nutritionally significant oilseed crops grown worldwide (Rajpoot *et al.,* 2020; Shrivastava *et al.,* 2023a). It is a frequently cross-pollinated crop, with outcrossing rates varying from 5–30% depending on environmental conditions and the activity of pollinating insects (Shrimali *et al*., 2016; Verma *et al*., 2021). In the Indian subcontinent, six species of rapeseed–mustard occur, with Indian mustard (*Brassica juncea*) dominating cultivation (Barfa *et al.,* 2017; Baghel *et al.,* 2020). Rapeseed and mustard together constitute the second most important group of oilseed crops worldwide after soybean (Food and Agriculture Organization [FAO], 2025). Mustard seeds contain approximately 38–46% oil, which is yellow, aromatic and widely regarded as one of the healthiest and most nutritious cooking oils (Vaghela *et al*., 2011; Shyam & Tripathi, 2019). This crop plays a crucial role in meeting the growing demand for edible oils, serving as a major source of vegetable oil for human consumption and as a valuable component of livestock feed (Rajpoot *et al.,* 2022; Shrivastav *et al.,* 2023b). Its adaptability to low-input farming systems, combined with comparatively modest fertilizer and water requirements, makes it suitable for resource-constrained farmers (Shyam *et al.,* 2020; Shrivastava *et al.,* 2023c; Kumari *et al.,* 2026). Moreover, its ability to fit into diverse cropping systems, for example as a *Rabi* (winter) crop following cereals such as rice and pearl millet, enhances its importance in sustainable agricultural practices (Shyam *et al*., 2021; Shrivastava *et al.,* 2023d).

Despite its considerable economical and ecological significance, rapeseed–mustard productivity in India remains significantly lower than its achievable potential (Sharma *et al*., 2025a). This yield gap is largely caused by an array of biotic and abiotic stresses (Yadav *et al*., 2019; Sharma *et al*., 2025b; Shrivastava *et al.,* 2023e; Shrivastav *et al.,* 2024; Dhakar *et al*., 2026). Another major limitation is the comparatively narrow genetic base of cultivated mustard varieties, which limits the scope for genetic gains through conventional selection. Reduced genetic diversity hampers the development of varieties with enhanced stress tolerance, yield potential and quality attributes (Sharma *et al*., 2025c).

Recent assessments have reported exploitable variability and trait associations among yield components in Indian mustard, with the number of siliquae, branching, test weight and related attributes providing useful selection information (Anita *et al.*, 2024; Gaur *et al.*, 2026). Diallel and line × tester studies have also indicated important roles of combining ability and non-additive gene action in the expression of seed yield and associated traits (Mandal *et al.*, 2023; Rout *et al.*, 2025; Patiyal *et al.*, 2025). However, these studies have not addressed the specific comparative framework of the present investigation, which evaluates 40 cross combinations against both zonal and national checks across 16 phenological, architectural and yield-related traits.

Therefore, there is an urgent need to broaden the genetic base and explore advanced breeding strategies, such as heterosis breeding and interspecific hybridization, to overcome these constraints (Tripathi *et al.,* 2015). Heterosis breeding has emerged as one of the most effective strategies for overcoming current limitations in yield performance (Meena *et al*., 2015). The term heterosis was introduced by Shull (1914) and refers to the superiority of the F_1 hybrid over its corresponding parents. Understanding heterosis is crucial for exploiting non-fixable gene effects in crop-improvement programmes and for achieving genetic gains in seed yield and its component traits. The degree of heterosis provides a basis for selecting superior parents to produce outstanding F_1 hybrids and for developing gene pools that can be utilized in breeding programmes to assess genetic diversity (Singh *et al*., 2024). Against this background, the present study was undertaken to evaluate the performance of 40 cross combinations of Indian mustard, together with zonal and national checks, with the objective of assessing heterosis for seed yield and yield-attributing traits. The findings are expected to identify superior hybrid combinations and provide insights into the genetic architecture of major yield and physiological traits, thereby aiding the formulation of effective breeding strategies to improve Indian mustard.

2. Material and methods

The present study was conducted at the Experimental Farm, Zonal Agricultural Research Station, Morena, Rajmata Vijaya Raje Scindia Agricultural University, Gwalior, Madhya Pradesh, India, during *Rabi* 2025 and 2026. During *Rabi* 2025, 40 diverse cross combinations were produced manually by hybridizing selected parents, including Pusa Bold, Varuna, Rohini, Kranti, Krishna, Maya, Vardan, Vasundhara, Swarn Jyoti, Pusa Jagannath, PM-26, PM-28, Pusa Vijay and NPJ-253, obtained from the All India Coordinated Research Project on Rapeseed & Mustard, Zonal Agricultural Research Station, Morena, RVSKVV, Gwalior, Madhya Pradesh, India. The resulting F_1 hybrids were subsequently evaluated during *Rabi* 2026 in a randomized block design (RBD) with three replications. The experiment was laid out with a spacing of 30 cm between rows and 10 cm between plants. All recommended agronomical practices were followed to raise a healthy crop. Observations were recorded for 16 quantitative traits, including days to flower initiation, days to 50% flowering, days to siliquae initiation, days to maturity, plant height, main raceme length, number of primary and secondary branches per plant, number of siliquae on the main raceme, number of siliquae per plant, number of seeds per siliquae, siliquae length, 1000-seed weight, biological yield per plant, harvest index and seed yield per plant. Data on yield and yield-related traits were recorded from 10 randomly selected plants for each cross combination in each replication. The observations were statistically analyzed according to the methods described by Tripathi *et al*. (2025).

3. Results and discussion

In the present study, standard heterosis was computed for all 16 traits as the percentage increase or decrease in the mean performance of different cross combinations over the zonal check (Maya) and national check (Kranti). The results of standard heterosis obtained over both checks are presented in Tables 1–8.

Table 1. Standard heterosis for days to flower initiation and days to 50% flowering

Cross combinations	DFI	HZC	HNC	DFF	HZC	HNC
Pusa Bold × PM-26	41.5	-9.78**	-14.43**	49.5	-12.39**	-14.66**
Pusa Bold × PM-28	46	0	-5.15**	54.5	-3.54**	-6.03**
Pusa Bold × Pusa Vijay	42	-8.7**	-13.4**	49.5	-12.39**	-14.66**
Pusa Bold × NPJ-253	44.5	-3.26**	-8.25**	56.5	0	-2.59*
Varuna × PM-26	41	-10.87**	-15.46**	49.5	-12.39**	-14.66**
Varuna × PM-28	39.5	-14.13**	-18.56**	49	-13.27**	-15.52**
Varuna × Pusa Vijay	39	-15.22**	-19.59**	48.5	-14.16**	-16.38**
Varuna × NPJ-253	39.5	-14.13**	-18.56**	50	-11.5**	-13.79**
Rohini × PM-26	40	-13.04**	-17.53**	50.5	-10.62**	-12.93**
Rohini × PM-28	39	-15.22**	-19.59**	49.5	-12.39**	-14.66**
Rohini × Pusa Vijay	41	-10.87**	-15.46**	52	-7.96**	-10.34**
Rohini × NPJ-253	42	-8.7**	-13.4**	51	-9.73**	-12.07**
Kranti × PM-26	42	-8.7**	-13.4**	50.5	-10.62**	-12.93**
Kranti × PM-28	42	-8.7**	-13.4**	51.5	-8.85**	-11.21**
Kranti × Pusa Vijay	44	-4.35**	-9.28**	55	-2.65*	-5.17**
Kranti × NPJ-253	40.5	-11.96**	-16.49**	50.5	-10.62**	-12.93**
Krishna × PM-26	50	8.7**	3.09**	57.5	1.77	-0.86
Krishna × PM-28	48	4.35**	-1.03	56.5	0	-2.59*
Krishna × Pusa Vijay	48	4.35**	-1.03	58	2.65*	0
Krishna × NPJ-253	48	4.35**	-1.03	58	2.65*	0
Maya × PM-26	44	-4.35**	-9.28**	56	-0.88	-3.45**
Maya × PM-28	44.5	-3.26**	-8.25**	54.5	-3.54**	-6.03**
Maya × Pusa Vijay	44	-4.35**	-9.28**	55.5	-1.77	-4.31**
Maya × NPJ-253	44.5	-3.26**	-8.25**	52.5	-7.08**	-9.48**
Vardan × PM-26	48	4.35**	-1.03	57.5	1.77	-0.86
Vardan × PM-28	48	4.35**	-1.03	57.5	1.77	-0.86
Vardan × Pusa Vijay	48	4.35**	-1.03	56	-0.88	-3.45**
Vardan × NPJ-253	45	-2.17	-7.22**	56	-0.88	-3.45**
Vasundhara × PM-26	48	4.35**	-1.03	56.5	0	-2.59*
Vasundhara × PM-28	52.5	14.13**	8.25**	61.5	8.85**	6.03**
Vasundhara × Pusa Vijay	46	0	-5.15**	55	-2.65*	-5.17**
Vasundhara × NPJ-253	46	0	-5.15**	55.5	-1.77	-4.31**
Swarn Jyoti × PM-26	48	4.35**	-1.03	59	4.42**	1.72
Swarn Jyoti × PM-28	48	4.35**	-1.03	60.5	7.08**	4.31**
Swarn Jyoti × Pusa Vijay	48	4.35**	-1.03	58	2.65*	0
Swarn Jyoti × NPJ-253	44	-4.35**	-9.28**	53.5	-5.31**	-7.76**
Pusa Jagannath × PM-26	41.5	-9.78**	-14.43**	51.5	-8.85**	-11.21**
Pusa Jagannath × PM-28	49.5	7.61**	2.06	57.5	1.77	-0.86
Pusa Jagannath × Pusa Vijay	40	-13.04**	-17.53**	50	-11.5**	-13.79**
Pusa Jagannath × NPJ-253	43	-6.52**	-11.34**	52.5	-7.08**	-9.48**
Maya (ZC)	46	-	-	56.5	-	-
Kranti (NC)	48.5	-	-	58	-	-
SE	0.49	-	-	0.77	-	-

**, ** indicates significance at 5% and 1% level, respectively; HZC: indicates heterosis over zonal check; HNC: indicates heterosis over national check; SE: Standard Error.*

Table 2. Standard heterosis for days to siliquae initiation and days to maturity

Cross combinations	DSI	HZC	HNC	DM	HZC	HNC
Pusa Bold × PM-26	54	-13.6**	-14.96**	131.5	-5.05**	-4.01**
Pusa Bold × PM-28	58.5	-6.4**	-7.87**	138.5	0	1.09
Pusa Bold × Pusa Vijay	56	-10.4**	-11.81**	135	-2.53**	-1.46*
Pusa Bold × NPJ-253	60	-4*	-5.51**	139.5	0.72	1.82*
Varuna × PM-26	55	-12**	-13.39**	134.5	-2.89**	-1.82*
Varuna × PM-28	53	-15.2**	-16.54**	132.5	-4.33**	-3.28**

Cross combinations	DSI	HZC	HNC	DM	HZC	HNC
Varuna × Pusa Vijay	53.5	-14.4**	-15.75**	131	-5.42**	-4.38**
Varuna × NPJ-253	53	-15.2**	-16.54**	132.5	-4.33**	-3.28**
Rohini × PM-26	55	-12**	-13.39**	134	-3.25**	-2.19**
Rohini × PM-28	55	-12**	-13.39**	135	-2.53**	-1.46*
Rohini × Pusa Vijay	56	-10.4**	-11.81**	135.5	-2.17**	-1.09
Rohini × NPJ-253	55	-12**	-13.39**	135	-2.53**	-1.46*
Kranti × PM-26	55	-12**	-13.39**	135.5	-2.17**	-1.09
Kranti × PM-28	56	-10.4**	-11.81**	136.5	-1.44*	-0.36
Kranti × Pusa Vijay	58.5	-6.4**	-7.87**	138.5	0	1.09
Kranti × NPJ-253	54	-13.6**	-14.96**	136.5	-1.44*	-0.36
Krishna × PM-26	61	-2.4	-3.94*	140.5	1.44*	2.55**
Krishna × PM-28	60.5	-3.2*	-4.72**	139.5	0.72	1.82*
Krishna × Pusa Vijay	62.5	0	-1.57	141.5	2.17**	3.28**
Krishna × NPJ-253	62	-0.8	-2.36	140.5	1.44*	2.55**
Maya × PM-26	60	-4*	-5.51**	138.5	0	1.09
Maya × PM-28	58	-7.2**	-8.66**	135.5	-2.17**	-1.09
Maya × Pusa Vijay	60	-4*	-5.51**	139.5	0.72	1.82*
Maya × NPJ-253	58	-7.2**	-8.66**	135.5	-2.17**	-1.09
Vardan × PM-26	61.5	-1.6	-3.15*	136.5	-1.44*	-0.36
Vardan × PM-28	63	0.8	-0.79	141	1.81*	2.92**
Vardan × Pusa Vijay	61	-2.4	-3.94*	132	-4.69**	-3.65**
Vardan × NPJ-253	60	-4*	-5.51**	134	-3.25**	-2.19**
Vasundhara × PM-26	62	-0.8	-2.36	139.5	0.72	1.82*
Vasundhara × PM-28	65	4*	2.36	141.5	2.17**	3.28**
Vasundhara × Pusa Vijay	59	-5.6**	-7.09**	133.5	-3.61**	-2.55**
Vasundhara × NPJ-253	61	-2.4	-3.94*	139.5	0.72	1.82*
Swarn Jyoti × PM-26	61.5	-1.6	-3.15*	135.5	-2.17**	-1.09
Swarn Jyoti × PM-28	62	-0.8	-2.36	140	1.08	2.19**
Swarn Jyoti × Pusa Vijay	62	-0.8	-2.36	137.5	-0.72	0.36
Swarn Jyoti × NPJ-253	58	-7.2**	-8.66**	130.5	-5.78**	-4.74**
Pusa Jagannath × PM-26	56	-10.4**	-11.81**	127.5	-7.94**	-6.93**
Pusa Jagannath × PM-28	62	-0.8	-2.36	134.5	-2.89**	-1.82*
Pusa Jagannath × Pusa Vijay	54	-13.6**	-14.96**	131.5	-5.05**	-4.01**
Pusa Jagannath × NPJ-253	56	-10.4**	-11.81**	132.5	-4.33**	-3.28**
Maya (ZC)	62.5	-	-	138.5	-	-
Kranti (NC)	63.5	-	-	137	-	-
SE	0.65	-	-	0.95	-	-

**, ** indicates significance at 5% and 1% level, respectively; HZC: indicates heterosis over zonal check; HNC: indicates heterosis over national check; SE: Standard Error*

Table 3. Standard heterosis for plant height and length of main raceme

Cross combinations	PH (cm)	HZC	HNC	MRL (cm)	HZC	HNC
Pusa Bold × PM-26	212.2	-2.43	-11.74**	63.95	-14.02**	-16.88**
Pusa Bold × PM-28	208.43	-4.16*	-13.31**	71.75	-3.54	-6.75**
Pusa Bold × Pusa Vijay	206.52	-5.04*	-14.1**	64.13	-13.78**	-16.65**
Pusa Bold × NPJ-253	205	-5.74**	-14.73**	67.43	-9.34**	-12.36**
Varuna × PM-26	232.4	6.86**	-3.34	80.66	8.44**	4.83*
Varuna × PM-28	230.4	5.94**	-4.17*	57.16	-23.15**	-25.71**
Varuna × Pusa Vijay	240.62	10.64**	0.08	75.3	1.24	-2.13
Varuna × NPJ-253	210.85	-3.05	-12.3**	75.33	1.28	-2.09
Rohini × PM-26	250.32	15.1**	4.12*	81.55	9.64**	5.99**
Rohini × PM-28	230.98	6.21**	-3.93*	82.63	11.09**	7.4**
Rohini × Pusa Vijay	240.7	10.68**	0.12	83.5	12.26**	8.53**
Rohini × NPJ-253	207.52	-4.58*	-13.68**	69.76	-6.21**	-9.33**
Kranti × PM-26	208.93	-3.93	-13.1**	67.76	-8.9**	-11.93**
Kranti × PM-28	214.38	-1.43	-10.83**	70.63	-5.04*	-8.2**
Kranti × Pusa Vijay	220.42	1.35	-8.32**	71.26	-4.19	-7.38**
Kranti × NPJ-253	207.88	-4.41*	-13.53**	65.6	-11.8**	-14.74**
Krishna × PM-26	240.08	10.39**	-0.14	60.93	-18.08**	-20.81**
Krishna × PM-28	223.8	2.91	-6.91**	73.16	-1.64	-4.91*
Krishna × Pusa Vijay	221.55	1.87	-7.85**	68.16	-8.36**	-11.41**
Krishna × NPJ-253	239.52	10.13**	-0.37	61.3	-17.59**	-20.33**
Maya × PM-26	212.45	-2.31	-11.63**	65.87	-11.44**	-14.39**

Cross combinations	PH (cm)	HZC	HNC	MRL (cm)	HZC	HNC
Maya × PM-28	231.98	6.67**	-3.51	72.5	-2.53	-5.77**
Maya × Pusa Vijay	226.55	4.17*	-5.77**	75.56	1.59	-1.79
Maya × NPJ-253	212.6	-2.24	-11.57**	60.83	-18.22**	-20.94**
Vardan × PM-26	220.55	1.41	-8.26**	61.93	-16.74**	-19.51**
Vardan × PM-28	184.06	-15.37**	-23.44**	63.66	-14.41**	-17.26**
Vardan × Pusa Vijay	183.68	-15.54**	-23.6**	63.12	-15.14**	-17.96**
Vardan × NPJ-253	203.98	-6.21**	-15.16**	68.5	-7.91**	-10.97**
Vasundhara × PM-26	236.39	8.7**	-1.68	83.47	12.22**	8.49**
Vasundhara × PM-28	200.45	-7.83**	-16.63**	66.23	-10.96**	-13.92**
Vasundhara × Pusa Vijay	222.72	2.41	-7.36**	73.23	-1.55	-4.82*
Vasundhara × NPJ-253	207.58	-4.55*	-13.66**	70.3	-5.49*	-8.63**
Swarn Jyoti × PM-26	225.4	3.64	-6.25**	67.76	-8.9**	-11.93**
Swarn Jyoti × PM-28	227.52	4.62*	-5.37**	67.37	-9.42**	-12.44**
Swarn Jyoti × Pusa Vijay	217.35	-0.06	-9.6**	62.23	-16.34**	-19.12**
Swarn Jyoti × NPJ-253	234.3	7.73**	-2.55	74.06	-0.43	-3.74
Pusa Jagannath × PM-26	222.95	2.52	-7.27**	61.97	-16.68**	-19.46**
Pusa Jagannath × PM-28	223	2.54	-7.25**	64.9	-12.75**	-15.65**
Pusa Jagannath × Pusa Vijay	220.49	1.38	-8.29**	75.7	1.77	-1.61
Pusa Jagannath × NPJ-253	217.45	-0.01	-9.55**	63.47	-14.67**	-17.51**
Maya (ZC)	217.48	-	-	74.38	-	-
Kranti (NC)	240.42	-	-	76.94	-	-
SE	4.75	-	-	1.77	-	-

**, ** indicates significance at 5% and 1% level, respectively; HZC: indicates heterosis over zonal check; HNC: indicates heterosis over national check; SE: Standard Error*

Table 4. Standard heterosis for number of primary branches per plant and number of secondary branches per plant

Cross combinations	PB	HZC	HNC	SB	HZC	HNC
Pusa Bold × PM-26	6.8	26.39**	20.14**	13.86	33.65**	15.02**
Pusa Bold × PM-28	7.78	44.61**	37.46**	18.3	76.47**	51.87**
Pusa Bold × Pusa Vijay	7	30.11**	23.67**	18.76	80.91**	55.68**
Pusa Bold × NPJ-253	5.62	4.46	-0.71	10.63	2.51	-11.78*
Varuna × PM-26	5.43	0.93	-4.06	12.9	24.4**	7.05
Varuna × PM-28	6.59	22.49**	16.43**	13.63	31.44**	13.11*
Varuna × Pusa Vijay	6.56	21.93**	15.9**	15.11	45.71**	25.39**
Varuna × NPJ-253	5.78	7.43	2.12	10	-3.57	-17.01**
Rohini × PM-26	6.54	21.56**	15.55**	16.93	63.26**	40.5**
Rohini × PM-28	7.3	35.69**	28.98**	19.23	85.44**	59.59**
Rohini × Pusa Vijay	6.56	21.93**	15.9**	14.16	36.55**	17.51**
Rohini × NPJ-253	4.69	-12.83*	-17.14**	7.7	-25.75**	-36.1**
Kranti × PM-26	5.6	4.09	-1.06	10.37	0	-13.94*
Kranti × PM-28	5.54	2.97	-2.12	8.46	-18.42**	-29.79**
Kranti × Pusa Vijay	5.89	9.48	4.06	12.75	22.95**	5.81
Kranti × NPJ-253	6.57	22.12**	16.08**	10.37	0	-13.94*
Krishna × PM-26	6.58	22.3**	16.25**	11.27	8.68	-6.47
Krishna × PM-28	8.17	51.86**	44.35**	15.23	46.87**	26.39**
Krishna × Pusa Vijay	7.6	41.26**	34.28**	12.27	18.32**	1.83
Krishna × NPJ-253	7.42	37.92**	31.1**	13.03	25.65**	8.13
Maya × PM-26	5.84	8.55	3.18	11.83	14.08*	-1.83
Maya × PM-28	5.26	-2.23	-7.07	9.83	-5.21	-18.42**
Maya × Pusa Vijay	6.46	20.07**	14.13*	11.37	9.64	-5.64
Maya × NPJ-253	6.08	13.01*	7.42	12.3	18.61**	2.07
Vardan × PM-26	5.6	4.09	-1.06	7.83	-24.49**	-35.02**
Vardan × PM-28	5.34	-0.74	-5.65	7.43	-28.35**	-38.34**
Vardan × Pusa Vijay	6.97	29.55**	23.14**	10.04	-3.18	-16.68**
Vardan × NPJ-253	6.22	15.61**	9.89	9.68	-6.65	-19.67**
Vasundhara × PM-26	7.39	37.36**	30.57**	17.4	67.79**	44.4**
Vasundhara × PM-28	4.84	-10.04	-14.49**	6.43	-37.99**	-46.64**
Vasundhara × Pusa Vijay	5.19	-3.53	-8.3	6.4	-38.28**	-46.89**
Vasundhara × NPJ-253	5.58	3.72	-1.41	12.33	18.9**	2.32

Cross combinations	PB	HZC	HNC	SB	HZC	HNC
Swarn Jyoti × PM-26	5.64	4.83	-0.35	9.2	-11.28	-23.65**
Swarn Jyoti × PM-28	4.77	-11.34*	-15.72**	5.86	-43.49**	-51.37**
Swarn Jyoti × Pusa Vijay	4.82	-10.41	-14.84**	5.36	-48.31**	-55.52**
Swarn Jyoti × NPJ-253	4.79	-10.97	-15.37**	5.94	-42.72**	-50.71**
Pusa Jagannath × PM-26	5.22	-2.97	-7.77	5.43	-47.64**	-54.94**
Pusa Jagannath × PM-28	4.94	-8.18	-12.72*	5.73	-44.74**	-52.45**
Pusa Jagannath × Pusa Vijay	4.97	-7.62	-12.19*	7.1	-31.53**	-41.08**
Pusa Jagannath × NPJ-253	5.28	-1.86	-6.71	7.33	-29.32**	-39.17**
Maya (ZC)	5.38	-	-	10.37	-	-
Kranti (NC)	5.66	-	-	12.05	-	-
SE	0.3	-	-	0.66	-	-

**, ** indicates significance at 5% and 1% level, respectively; HZC: indicates heterosis over zonal check; HNC: indicates heterosis over national check; SE: Standard Error*

Table 5. Standard heterosis for number of siliquae on main raceme and number of siliquae per plant

Cross combinations	SMR (No.)	HZC	HNC	SPP (No.)	HZC	HNC
Pusa Bold × PM-26	43.64	-13.91**	-17.24**	316.24	-17.57**	-20.48**
Pusa Bold × PM-28	53.57	5.68*	1.59	513.42	33.83**	29.09**
Pusa Bold × Pusa Vijay	49.75	-1.85	-5.65*	524	36.58**	31.75**
Pusa Bold × NPJ-253	44.45	-12.31**	-15.7**	268.6	-29.99**	-32.46**
Varuna × PM-26	45.97	-9.31**	-12.82**	345.36	-9.98**	-13.16**
Varuna × PM-28	42.09	-16.97**	-20.18**	495.23	29.08**	24.52**
Varuna × Pusa Vijay	46.09	-9.07**	-12.59**	474.73	23.74**	19.37**
Varuna × NPJ-253	42.64	-15.88**	-19.14**	532.72	38.86**	33.95**
Rohini × PM-26	60.74	19.83**	15.19**	518.5	35.15**	30.37**
Rohini × PM-28	52.62	3.81	-0.21	533.73	39.12**	34.2**
Rohini × Pusa Vijay	64.49	27.22**	22.3**	426.88	11.27**	7.33**
Rohini × NPJ-253	40.94	-19.23**	-22.36**	231.26	-39.72**	-41.85**
Kranti × PM-26	44.34	-12.53**	-15.91**	207.97	-45.79**	-47.71**
Kranti × PM-28	49.3	-2.74	-6.5*	264.56	-31.04**	-33.48**
Kranti × Pusa Vijay	52.51	3.59	-0.42	288.28	-24.86**	-27.52**
Kranti × NPJ-253	48.75	-3.83	-7.55**	499.98	30.32**	25.71**
Krishna × PM-26	51.17	0.95	-2.96	322.88	-15.84**	-18.82**
Krishna × PM-28	50.07	-1.22	-5.04*	315.24	-17.83**	-20.74**
Krishna × Pusa Vijay	44.08	-13.04**	-16.4**	308.86	-19.49**	-22.34**
Krishna × NPJ-253	55.21	8.92**	4.7	231.67	-39.61**	-41.75**
Maya × PM-26	45.55	-10.14**	-13.62**	274.29	-28.51**	-31.03**
Maya × PM-28	59.34	17.06**	12.54**	223.48	-41.75**	-43.81**
Maya × Pusa Vijay	56.03	10.53**	6.26*	505.32	31.71**	27.06**
Maya × NPJ-253	50.26	-0.85	-4.68	280.44	-26.9**	-29.49**
Vardan × PM-26	38.48	-24.09**	-27.02**	287.06	-25.18**	-27.82**
Vardan × PM-28	40.12	-20.85**	-23.91**	220.44	-42.54**	-44.57**
Vardan × Pusa Vijay	40.7	-19.71**	-22.81**	307.38	-19.88**	-22.71**
Vardan × NPJ-253	45.88	-9.49**	-12.99**	284.76	-25.78**	-28.4**
Vasundhara × PM-26	55.36	9.21**	4.99*	530.36	38.24**	33.35**
Vasundhara × PM-28	44.66	-11.9**	-15.3**	210.57	-45.11**	-47.05**
Vasundhara × Pusa Vijay	47	-7.28**	-10.87**	327.12	-14.73**	-17.75**
Vasundhara × NPJ-253	57.81	14.05**	9.63**	351.04	-8.5**	-11.73**
Swarn Jyoti × PM-26	53.87	6.27*	2.16	249.01	-35.09**	-37.39**
Swarn Jyoti × PM-28	47.81	-5.68*	-9.33**	278.09	-27.51**	-30.08**
Swarn Jyoti × Pusa Vijay	46.26	-8.74**	-12.27**	242.14	-36.89**	-39.12**
Swarn Jyoti × NPJ-253	51.36	1.32	-2.6	257.98	-32.76**	-35.13**
Pusa Jagannath × PM-26	48.05	-5.21*	-8.88**	218.09	-43.15**	-45.16**
Pusa Jagannath × PM-28	38.67	-23.71**	-26.66**	237.06	-38.21**	-40.39**
Pusa Jagannath × Pusa Vijay	47.16	-6.96**	-10.56**	280.8	-26.81**	-29.4**
Pusa Jagannath × NPJ-253	41.19	-18.74**	-21.89**	266.9	-30.43**	-32.89**
Maya (ZC)	50.69	-	-	383.65	-	-
Kranti (NC)	52.73	-	-	397.71	-	-
SE	1.3	-	-	7.22	-	-

**, ** indicates significance at 5% and 1% level, respectively; HZC: indicates heterosis over zonal check; HNC: indicates heterosis over national check; SE: Standard Error*

Table 6. Standard heterosis for number of seeds per siliquae and siliquae length

Cross combinations	SPS (No.)	HZC	HNC	LS (cm)	HZC	HNC
Pusa Bold × PM-26	14.05	0.36	2.55	4.7	1.51	6.33
Pusa Bold × PM-28	14.5	3.57	5.84	4.4	-4.97	-0.45
Pusa Bold × Pusa Vijay	14.11	0.79	2.99	4.1	-11.45**	-7.24
Pusa Bold × NPJ-253	10.8	-22.86**	-21.17**	4.25	-8.21*	-3.85
Varuna × PM-26	11.43	-18.36**	-16.57**	4.9	5.83	10.86**
Varuna × PM-28	14.16	1.14	3.36	5.2	12.31**	17.65**
Varuna × Pusa Vijay	14.1	0.71	2.92	5.55	19.87**	25.57**
Varuna × NPJ-253	11.38	-18.71**	-16.93**	5.05	9.07*	14.25**
Rohini × PM-26	14.34	2.43	4.67	4.9	5.83	10.86**
Rohini × PM-28	12.31	-12.07**	-10.15**	5.1	10.15**	15.38**
Rohini × Pusa Vijay	15.13	8.07*	10.44**	5.25	13.39**	18.78**
Rohini × NPJ-253	12.43	-11.21**	-9.27**	4.71	1.73	6.56
Kranti × PM-26	13.44	-4	-1.9	4.7	1.51	6.33
Kranti × PM-28	10.38	-25.86**	-24.23**	4.12	-11.02**	-6.79
Kranti × Pusa Vijay	13.35	-4.64	-2.55	4.5	-2.81	1.81
Kranti × NPJ-253	11.31	-19.21**	-17.45**	4.35	-6.05	-1.58
Krishna × PM-26	12.6	-10**	-8.03*	4.2	-9.29*	-4.98
Krishna × PM-28	13.54	-3.29	-1.17	4.53	-2.16	2.49
Krishna × Pusa Vijay	15.41	10.07**	12.48**	4.4	-4.97	-0.45
Krishna × NPJ-253	12.82	-8.43*	-6.42	5.47	18.14**	23.76**
Maya × PM-26	14.22	1.57	3.8	5.1	10.15**	15.38**
Maya × PM-28	11.18	-20.14**	-18.39**	3.91	-15.55**	-11.54**
Maya × Pusa Vijay	14.46	3.29	5.55	4.5	-2.81	1.81
Maya × NPJ-253	13.91	-0.64	1.53	5.65	22.03**	27.83**
Vardan × PM-26	12.84	-8.29*	-6.28	4.5	-2.81	1.81
Vardan × PM-28	13.41	-4.21	-2.12	5.3	14.47**	19.91**
Vardan × Pusa Vijay	12.29	-12.21**	-10.29**	5.25	13.39**	18.78**
Vardan × NPJ-253	15.38	9.86**	12.26**	5.28	14.04**	19.46**
Vasundhara × PM-26	14.41	2.93	5.18	4.91	6.05	11.09**
Vasundhara × PM-28	14.23	1.64	3.87	4.95	6.91	11.99**
Vasundhara × Pusa Vijay	14.68	4.86	7.15*	5.4	16.63**	22.17**
Vasundhara × NPJ-253	13.16	-6	-3.94	5.1	10.15**	15.38**
Swarn Jyoti × PM-26	15.29	9.21**	11.61**	5	7.99*	13.12**
Swarn Jyoti × PM-28	12.65	-9.64**	-7.66*	4.4	-4.97	-0.45
Swarn Jyoti × Pusa Vijay	13.16	-6	-3.94	4.32	-6.7	-2.26
Swarn Jyoti × NPJ-253	12.46	-11**	-9.05**	4.86	4.97	9.95*
Pusa Jagannath × PM-26	13.16	-6	-3.94	4.55	-1.73	2.94
Pusa Jagannath × PM-28	14.82	5.86	8.18*	4.78	3.24	8.14*
Pusa Jagannath × Pusa Vijay	15.39	9.93**	12.34**	4.61	-0.43	4.3
Pusa Jagannath × NPJ-253	15.05	7.5*	9.85**	5.25	13.39**	18.78**
Maya (ZC)	14	-	-	4.63	-	-
Kranti (NC)	13.7	-	-	4.42	-	-
SE	0.44	-	-	0.18	-	-

**, ** indicates significance at 5% and 1% level, respectively; HZC: indicates heterosis over zonal check; HNC: indicates heterosis over national check; SE: Standard Error*

Table 7. Standard heterosis for test weight (1000- seeds weight) and biological yield per plant

Cross combinations	TW (g)	HZC	HNC	BYPP (g)	HZC	HNC
Pusa Bold × PM-26	5.26	6.91	1.15	74.15	-9.1**	-7.97**
Pusa Bold × PM-28	4.57	-7.11	-12.12**	92.42	13.3**	14.71**
Pusa Bold × Pusa Vijay	5.45	10.77*	4.81	114.12	39.9**	41.64**
Pusa Bold × NPJ-253	5.96	21.14**	14.62**	46.62	-42.85**	-42.14**
Varuna × PM-26	5.06	2.85	-2.69	77.15	-5.42**	-4.24*
Varuna × PM-28	5.34	8.54	2.69	101.53	24.47**	26.01**
Varuna × Pusa Vijay	5.31	7.93	2.12	103.97	27.46**	29.04**
Varuna × NPJ-253	5.4	9.76*	3.85	95.95	17.63**	19.09**
Rohini × PM-26	5.28	7.32	1.54	100.15	22.78**	24.3**
Rohini × PM-28	4.48	-8.94*	-13.85**	101.12	23.97**	25.51**
Rohini × Pusa Vijay	5.88	19.51**	13.08**	95.17	16.67**	18.12**
Rohini × NPJ-253	5.47	11.18*	5.19	45.78	-43.88**	-43.18**
Kranti × PM-26	5.3	7.72	1.92	53.03	-34.99**	-34.18**
Kranti × PM-28	5.39	9.55*	3.65	56.08	-31.25**	-30.4**
Kranti × Pusa Vijay	6.35	29.07**	22.12**	74.05	-9.22**	-8.09**

Cross combinations	TW (g)	HZC	HNC	BYPP (g)	HZC	HNC
Kranti × NPJ-253	5.74	16.67**	10.38*	96.53	18.34**	19.81**
Krishna × PM-26	4.64	-5.69	-10.77*	71.95	-11.79**	-10.7**
Krishna × PM-28	4.94	0.41	-5	75.7	-7.2**	-6.04**
Krishna × Pusa Vijay	4.77	-3.05	-8.27	66.1	-18.97**	-17.96**
Krishna × NPJ-253	5.71	16.06**	9.81*	63.73	-21.87**	-20.9**
Maya × PM-26	5.76	17.07**	10.77*	74.4	-8.79**	-7.66**
Maya × PM-28	4.7	-4.47	-9.62*	51.52	-36.84**	-36.06**
Maya × Pusa Vijay	5.16	4.88	-0.77	98.05	20.2**	21.7**
Maya × NPJ-253	6.04	22.76**	16.15**	54.85	-32.76**	-31.92**
Vardan × PM-26	5.24	6.5	0.77	63.02	-22.74**	-21.78**
Vardan × PM-28	5.58	13.41**	7.31	35.78	-56.14**	-55.59**
Vardan × Pusa Vijay	5.96	21.14**	14.62**	69.85	-14.37**	-13.31**
Vardan × NPJ-253	6.2	26.02**	19.23**	57.65	-29.32**	-28.45**
Vasundhara × PM-26	5.09	3.46	-2.12	114.1	39.88**	41.62**
Vasundhara × PM-28	5.32	8.13	2.31	37.24	-54.35**	-53.78**
Vasundhara × Pusa Vijay	5.59	13.62**	7.5	65.75	-19.39**	-18.39**
Vasundhara × NPJ-253	5.58	13.41**	7.31	58.4	-28.41**	-27.52**
Swarn Jyoti × PM-26	5.42	10.16*	4.23	73.32	-10.11**	-9**
Swarn Jyoti × PM-28	6.06	23.17**	16.54**	53.92	-33.9**	-33.08**
Swarn Jyoti × Pusa Vijay	5.36	8.94*	3.08	64.78	-20.58**	-19.6**
Swarn Jyoti × NPJ-253	6.33	28.66**	21.73**	55.08	-32.48**	-31.64**
Pusa Jagannath × PM-26	5.16	4.88	-0.77	45.52	-44.2**	-43.5**
Pusa Jagannath × PM-28	5.57	13.21**	7.12	37.6	-53.9**	-53.33**
Pusa Jagannath × Pusa Vijay	5.83	18.5**	12.12**	61.85	-24.18**	-23.23**
Pusa Jagannath × NPJ-253	6.04	22.76**	16.15**	55.12	-32.43**	-31.59**
Maya (ZC)	4.92	-	-	81.57	-	-
Kranti (NC)	5.2	-	-	80.57	-	-
SE	0.21	-	-	1.5	-	-

**, ** indicates significance at 5% and 1% level, respectively; HZC: indicates heterosis over zonal check; HNC: indicates heterosis over national check; SE: Standard Error*

Table 8. Standard heterosis for harvest index and seed yield per plant

Cross combinations	HI (%)	HZC	HNC	SYPP (g)	HZC	HNC
Pusa Bold × PM-26	31.2	15.86**	4.56*	23.13	5.28	-3.83
Pusa Bold × PM-28	33.35	23.84**	11.76**	30.82	40.28**	28.15**
Pusa Bold × Pusa Vijay	29.46	9.39**	-1.27	33.62	53.03**	39.79**
Pusa Bold × NPJ-253	36.08	33.98**	20.91**	16.83	-23.4**	-30.02**
Varuna × PM-26	28.52	5.9*	-4.42*	22	0.14	-8.52**
Varuna × PM-28	31.42	16.67**	5.29*	31.9	45.2**	32.64**
Varuna × Pusa Vijay	26.35	-2.15	-11.7**	27.4	24.72**	13.93**
Varuna × NPJ-253	34.31	27.4**	14.98**	32.92	49.84**	36.88**
Rohini × PM-26	29.8	10.66**	-0.13	29.85	35.87**	24.12**
Rohini × PM-28	30.84	14.52**	3.35	31.18	41.92**	29.65**
Rohini × Pusa Vijay	28.68	6.5**	-3.89	27.3	24.26**	13.51**
Rohini × NPJ-253	29.05	7.87**	-2.65	13.3	-39.46**	-44.7**
Kranti × PM-26	31.26	16.08**	4.76*	16.58	-24.53**	-31.06**
Kranti × PM-28	33.52	24.47**	12.33**	18.8	-14.43**	-21.83**
Kranti × Pusa Vijay	31.57	17.23**	5.8**	23.38	6.42*	-2.79
Kranti × NPJ-253	32.89	22.13**	10.22**	31.75	44.52**	32.02**
Krishna × PM-26	29.84	10.81**	0	21.48	-2.23	-10.69**
Krishna × PM-28	29.62	9.99**	-0.74	22.42	2.05	-6.78**
Krishna × Pusa Vijay	28.9	7.32**	-3.15	19.1	-13.06**	-20.58**
Krishna × NPJ-253	31.38	16.52**	5.16*	20	-8.97**	-16.84**
Maya × PM-26	26.18	-2.78	-12.27**	19.48	-11.33**	-19**
Maya × PM-28	26.78	-0.56	-10.25**	13.8	-37.19**	-42.62**
Maya × Pusa Vijay	31.72	17.79**	6.3**	31.1	41.56**	29.31**
Maya × NPJ-253	29.67	10.17**	-0.57	16.27	-25.94**	-32.35**
Vardan × PM-26	31.86	18.31**	6.77**	20.08	-8.6**	-16.51**
Vardan × PM-28	35.8	32.94**	19.97**	12.78	-41.83**	-46.86**
Vardan × Pusa Vijay	32.78	21.72**	9.85**	22.9	4.23	-4.78
Vardan × NPJ-253	32.91	22.21**	10.29**	18.98	-13.61**	-21.08**
Vasundhara × PM-26	29.66	10.14**	-0.6	33.85	54.07**	40.75**
Vasundhara × PM-28	26.18	-2.78	-12.27**	9.75	-55.62**	-59.46**
Vasundhara × Pusa Vijay	32.21	19.61**	7.94**	21.18	-3.6	-11.93**
Vasundhara × NPJ-253	28.08	4.27	-5.9**	16.4	-25.35**	-31.81**

Cross combinations	HI (%)	HZC	HNC	SYPP (g)	HZC	HNC
Swarn Jyoti × PM-26	23.84	-11.47**	-20.11**	17.48	-20.44**	-27.32**
Swarn Jyoti × PM-28	32.77	21.69**	9.82**	17.68	-19.53**	-26.49**
Swarn Jyoti × Pusa Vijay	28.41	5.5*	-4.79*	18.4	-16.25**	-23.49**
Swarn Jyoti × NPJ-253	28.87	7.2**	-3.25	15.9	-27.63**	-33.89**
Pusa Jagannath × PM-26	31.52	17.04**	5.63**	14.35	-34.68**	-40.33**
Pusa Jagannath × PM-28	32.31	19.98**	8.28**	12.15	-44.7**	-49.48**
Pusa Jagannath × Pusa Vijay	33.95	26.07**	13.77**	21	-4.42	-12.68**
Pusa Jagannath × NPJ-253	30.2	12.14**	1.21	16.65	-24.21**	-30.77**
Maya (ZC)	26.93	-	-	26.93	-	-
Kranti (NC)	29.84	-	-	24.05	-	-
SE	0.61	-	-	0.64	-	-

**, ** indicates significance at 5% and 1% level, respectively; HZC: indicates heterosis over zonal check; HNC: indicates heterosis over national check; SE: Standard Error*

Standard heterosis for days to flower initiation (DFI) over the zonal check (Maya) ranged from -15.22% to 14.13%, while standard heterosis over the national check (Kranti) ranged from -19.59% to 8.25%. Among the 40 cross combinations evaluated, the hybrids Varuna × Pusa Vijay, Rohini × PM-28 and Varuna × PM-28 exhibited the highest statistically significant desirable heterosis in the negative direction for DFI. Standard heterosis for days to 50% flowering (DFF) over the zonal check (Maya) varied from -14.16% to 8.85%, while that over the national check (Kranti) varied from -16.38% to 6.03%. Notably, the crosses Varuna × Pusa Vijay, Varuna × PM-28 and Pusa Bold × PM-26 demonstrated the most desirable statistically significant negative heterosis values for DFF, indicating their potential for early flowering. For days to siliquae initiation (DSI), standard heterosis over the zonal check (Maya) ranged from -15.20% to 4.00%, while that over the national check (Kranti) ranged between -16.54% to 2.36%. Among the 40 cross combinations evaluated, the hybrids Varuna × PM-28, Varuna × NPJ-253 and Varuna × Pusa Vijay recorded the most desirable statistically significant negative heterosis values for DSI. For days to maturity (DM), standard heterosis ranged from -6.93% to 3.28% over the national check (Kranti) and from -7.94% to 2.17% over the zonal check (Maya). Among the evaluated crosses, Pusa Jagannath × PM-26, Swarn Jyoti × NPJ-253 and Varuna × Pusa Vijay exhibited the most desirable heterosis in the negative direction for DM. By reducing the duration to maturity, these hybrids demonstrated potential for earliness, which is advantageous in mustard breeding programmes. For plant height (PH), standard heterosis over the zonal check (Maya) ranged from -15.54% to 15.10%, while that over the national check (Kranti) varied from -23.60% to 4.12%. Because reduced plant height is desirable in mustard breeding to minimize lodging, negative heterosis is considered advantageous for this trait. Among the evaluated crosses, Vardan × Pusa Vijay, Vardan × PM-28 and Vasundhara × PM-28 exhibited the most desirable statistically significant negative heterosis for PH.

For main raceme length (MRL), standard heterosis over the zonal check (Maya) ranged from -23.15% to 12.26%, while that over the national check (Kranti) ranged from -25.71% to 8.53%. The three cross combinations showing the highest positive heterosis were Rohini × Pusa Vijay, Vasundhara × PM-26 and Rohini × PM-28. For the number of primary branches per plant (PB), standard heterosis over the zonal check (Maya) ranged from -12.83% to 51.86%, while that over the national check (Kranti) varied from -17.14% to 44.35%. Positive heterosis is desirable for this trait because a greater number of primary branches contributes to enhanced seed yield per plant. Among the evaluated crosses, Krishna × PM-28, Pusa Bold × PM-28 and Krishna × Pusa Vijay exhibited the most desirable statistically significant positive heterosis for PB. For the number of secondary branches per plant (SB), standard heterosis over the zonal check (Maya) ranged from -48.31% to 85.44%, while that over the national check (Kranti) varied from -55.52% to 59.59%. The crosses Rohini × PM-28, Pusa Bold × Pusa Vijay and Pusa Bold × PM-28 exhibited the highest statistically significant positive heterosis for SB. For the number of siliquae on the main raceme (SMR), standard heterosis over the zonal check (Maya) differed from -24.09% to 27.22%, while that over the national check (Kranti) varied from -27.02% to 22.30%. Positive heterosis is desirable for this trait because a higher number of siliquae on the main raceme contributes directly to enhanced reproductive efficiency and seed yield (Tripathi *et al*., 2025). The hybrids Rohini × Pusa Vijay, Rohini × PM-26 and Maya × PM-28 recorded the highest statistically significant positive heterosis for SMR. For the number of siliquae per plant (SPP), standard heterosis over the zonal check (Maya) ranged from -45.79% to 39.12%, while that over the national check (Kranti) varied from -47.71% to 34.20%. Positive heterosis is desirable for this trait because a higher number of siliquae per plant directly enhances seed-yield potential. The hybrids Rohini × PM-28, Varuna × NPJ-253 and Vasundhara × PM-26 exhibited the highest statistically significant positive heterosis for SPP. For the number of seeds per siliquae (SPS), standard heterosis over the zonal check (Maya) ranged from -25.86% to 10.07%, while that over the national check (Kranti) varied from -24.23% to 12.48%. Positive heterosis is desirable for this trait because a higher number of seeds per siliquae directly enhances seed-yield potential. The hybrids Krishna × Pusa Vijay, Pusa Jagannath × Pusa Vijay and Vardan × NPJ-253 exhibited the highest statistically significant positive heterosis values over both of the checks. For siliquae length (LS), standard heterosis over the zonal check (Maya) ranged from -15.55% to 22.03%, while that over the national check (Kranti) varied from -11.54% to 27.83%. Positive heterosis is desirable for this trait because longer siliquae generally accommodate more seeds, thereby contributing to enhanced seed yield. The hybrids Maya × NPJ-253, Varuna × Pusa Vijay and Krishna × NPJ-253 exhibited the highest statistically significant positive heterosis for LS. For test weight (TW), standard heterosis over the zonal check (Maya) ranged from -8.94% to 29.07%, while that over the national check (Kranti) varied from -13.85% to 22.12%. Positive heterosis is desirable for this trait because a higher test weight reflects greater seed size and quality. The hybrids Kranti × Pusa Vijay, Swarn Jyoti × NPJ-253 and Vardan × NPJ-253 exhibited the highest statistically significant positive heterosis for TW. For biological yield per plant (BYPP), standard heterosis over the zonal check (Maya) ranged from -56.14% to 39.90%, while that over the national check (Kranti) varied from -55.59% to 41.64%. Positive heterosis is desirable for this trait because a higher biological yield reflects greater overall biomass production, which is closely associated with enhanced seed-yield potential. The hybrids Pusa Bold × Pusa Vijay, Vasundhara × PM-26 and Varuna × Pusa Vijay exhibited the highest statistically significant positive heterosis over both checks. For harvest index (HI), standard heterosis over the zonal check (Maya) ranged from -11.47% to 33.98%, while that over the national check (Kranti) varied from -20.11% to 20.91%. Positive heterosis is desirable for this trait because a higher harvest index reflects improved partitioning efficiency to assimilates towards economic yield. The hybrids Pusa Bold × NPJ-253, Vardan × PM-28 and Varuna × NPJ-253 exhibited the highest statistically significant positive heterosis for HI. For seed yield per plant (SYPP), standard heterosis over the zonal check (Maya) ranged from -55.62% to 54.07%, while that over the national check (Kranti) varied from -59.46% to 40.75%. Positive heterosis is highly desirable for this trait because it directly reflects the genetic potential of hybrids to outperform the standard checks for seed-yield performance.

Several cross combinations, including Vasundhara × PM-26, Pusa Bold × Pusa Vijay, Varuna × NPJ-253, Varuna × PM-28, Kranti × NPJ-253, Rohini × PM-28, Maya × Pusa Vijay, Pusa Bold × PM-28, Rohini × PM-26, Varuna × Pusa Vijay and Rohini × Pusa Vijay, exhibited significant positive heterosis over both of the checks. These hybrids are promising candidates for yield improvement, highlighting their potential utility in Indian mustard breeding programmes aimed at enhancing productivity and meeting future demand. Heterosis plays a pivotal role in plant breeding programmes, particularly in enhancing seed yield and its component traits. The magnitude of the heterotic response is largely influenced by genetic variability, ecological conditions, and the diversity and origin of parental lines. In the present study, higher standard heterosis was observed for seed yield and related attributes, corroborating earlier findings reported by Chaudhary *et al.* (2018), Rout *et al*. (2018), Bhinda *et al.* (2020), Shekhawat *et al.* (2021), Kumawat *et al.* (2022), Kishore et al. (2025), Tripathi *et al. (*2025) and Kumari *et al.* (2026). These consistent findings across different environments and genetic backgrounds emphasize the importance of exploiting heterosis as a reliable breeding strategy for yield improvement in Indian mustard.

4. Conclusion

The evaluation of 40 Indian mustard cross combinations demonstrated substantial variation in standard heterosis for phenological, architectural and yield-related traits. Seed yield per plant showed positive standard heterosis of up to 54.07% over the zonal check Maya and 40.75% over the national check Kranti. Vasundhara × PM-26 was the leading cross for seed yield per plant, while Pusa Bold × Pusa Vijay, Varuna × NPJ-253, Varuna × PM-28, Kranti × NPJ-253, Rohini × PM-28, Maya × Pusa Vijay and Pusa Bold × PM-28 also performed favorably over both checks. Several other crosses exhibited desirable heterosis for earliness, reduced plant height, branching, siliquae number, seeds per siliquae, siliquae length, test weight, biological yield and harvest index. These results indicated that heterosis breeding can provide useful genetic combinations for improving seed yield and associated traits in Indian mustard.

5. Limitations

The experiment evaluated F_1 cross combinations at a single location during one evaluation season. Consequently, the stability of heterotic responses and genotype × environment interactions could not be assessed. The findings are therefore specific to the tested environment and checks. Multi-location and multi-season trials are required to confirm the consistency, adaptability and breeding value of the promising crosses.

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 no competing interests exist.

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