EXTANT OF HETEROSIS FOR SEED YIELD AND YIELD ATTRIBUTING TRAITS IN INDIAN MUSTARD (*BRASSICA JUNCEA* L. CZERN & COSS.) UNDER TIMELY AND LATE SOWN CONDITIONS

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ABSTRACT
Indian mustard (*Brassica juncea* (L.) Czern & Coss.) is one of the most important oilseed crops, contributing significantly to edible oil production in India. Exploiting heterosis through suitable parental combinations remains an effective strategy for enhancing seed yield and associated agronomic traits. The present investigation was undertaken to assess the magnitude of heterosis and identify promising hybrid combinations for seed yield and its contributing characters under contrasting environmental conditions. A set of ten genetically diverse parental genotypes and their forty-five F_1 hybrids, developed through a half-diallel mating design excluding reciprocals, were evaluated under two sowing environments, namely timely sown (E_1) and late sown (E_2), along with pooled analysis. The experimental material was assessed for seed yield and its component traits, including seeds per siliqua, 1000-seed weight, oil content, and other yield-related parameters. Analysis of variance revealed highly significant differences among treatments, parents, hybrids, and parent versus crosses for all the traits studied under individual as well as pooled environments, indicating the presence of substantial genetic variability and the existence of considerable heterotic potential among the parental lines. The magnitude of heterosis varied considerably among different crosses and traits, demonstrating the influence of parental genetic diversity and environmental conditions on hybrid performance. Significant positive mid-parent heterosis for seeds per siliqua and oil content was recorded in the cross HUJM-05-03 × SKM-0526, suggesting the presence of favourable non-additive gene action for these economically important traits. High and desirable better-parent heterosis (heterobeltiosis) for oil content was observed in the crosses Purple mutant × HUJM-05-03 and HUJM-05-03 × SKM-0526. Similarly, superior heterobeltiosis for seeds per siliqua was exhibited by Purple mutant × RKM-3 and RKM-3 × Varuna across timely sown, late sown, and pooled environments, indicating their stability and consistency under varying sowing conditions. Under the late-sown environment (E_2), where plants are exposed to terminal heat stress, the cross Maya × Varuna expressed significant positive heterosis for 1000-seed weight, reflecting its potential for maintaining seed development under stress conditions. For seed yield per plant, the crosses HUJM-05-03 × RKM-3 and RH-0512 × SKM-0526 emerged as the most promising combinations owing to their superior hybrid performance and desirable heterotic response. Nevertheless, none of the hybrid combinations consistently expressed significant positive heterosis over both the mid-parent and better parent simultaneously for all the traits investigated, highlighting the complex inheritance pattern and trait-specific nature of heterosis in Indian mustard. In present study identified several superior cross combinations possessing favourable heterotic effects for seed yield and its associated traits. These hybrids represent valuable genetic resources for the development of high-yielding and quality mustard cultivars and may serve as potential candidates for future breeding programmes aimed at exploiting hybrid vigour and improving productivity under diverse environmental conditions.

KEYWORDS: Brassica juncea, heterosis, heterobeltiosis, diallel analysis, seed yield, oil content, breeding

INTRODUCTION
Oilseed production holds critical importance in India due to the persistent imbalance between domestic demand and supply of edible oils. This gap has led to substantial imports, placing a considerable burden on foreign exchange reserves (FAOSTAT, 2021; Kumar et al., 2022). At present, oilseed crops are cultivated over approximately 25.74 million hectares, producing about 30.55 million tonnes with an average productivity of 1188 kg per hectare (DES, 2020). Among the major oilseed crops, rapeseed–mustard occupies a prominent position, contributing nearly one-fourth of the total edible oilseed

production and serving as a vital source of income for farmers, particularly in northern India (Kumar et al., 2022; Singh et al., 2017).

Indian mustard (*Brassica juncea* L. Czern & Coss) is well adapted to diverse agro-climatic conditions and plays a crucial role in ensuring edible oil security. However, its productivity is constrained by several factors, including a narrow genetic base, susceptibility to biotic and abiotic stresses, and suboptimal agronomic practices (Rakow and Woods, 1987; Singh et al., 2010). In regions like Uttar Pradesh, late sowing due to delayed harvesting of preceding crops often exposes the crop to terminal heat stress, significantly reducing yield (Kumar et al., 2018). Therefore, the development of high-yielding and stress-resilient varieties remains a key breeding objective.

Heterosis, or hybrid vigor, is a powerful genetic phenomenon widely utilized for yield enhancement. The study of heterosis provides essential insights into the genetic architecture of yield and its component traits, as well as the breeding potential of parental lines (Shull, 1908; Hayes et al., 1955). In a predominantly self-pollinated crop like Indian mustard, the exploitation of heterosis depends on its magnitude, direction, and the nature of gene action involved. Estimation of relative heterosis (over mid-parent) and heterobeltiosis (over better parent) is useful for identifying superior cross combinations (Fonseca and Patterson, 1968).

Furthermore, partitioning genetic variance into general combining ability (GCA) and specific combining ability (SCA) helps in understanding the relative importance of additive and non-additive gene effects (Griffing, 1956). The performance of F_1 hybrids is influenced by both fixable (additive) and non-fixable (dominance and epistatic) gene actions, which determine the scope for selection and hybrid development (Sprague and Tatum, 1942). Traits such as seed yield, oil content, seeds per siliqua, and 1000-seed weight are key determinants of productivity and economic value in mustard, necessitating their simultaneous improvement (Singh et al., 2017).

Diallel mating designs are effective tools for evaluating combining ability and identifying superior parents and cross combinations. Despite extensive research in mustard breeding, limited attention has been paid to environment-specific heterosis, particularly under contrasting sowing conditions such as timely and late sowing. Such evaluation is essential to identify stable and high-performing hybrids across environments (Allard, 1960; Falconer and Mackay, 1996).

In this context, the present study employs a half-diallel mating design to assess heterosis and combining ability among selected Indian mustard genotypes under contrasting environments. The objective is to identify promising heterotic cross combinations and superior parents for yield and oil-related traits, with particular emphasis on the agro-climatic conditions of Uttar Pradesh. The findings are expected to contribute to the development of high-yielding, high-oil mustard hybrids with improved adaptability, thereby supporting sustainable oilseed production and reducing import dependency.

MATERIALS AND METHODS

The present study was carried out at research field of the Department of Genetics and Plant Breeding, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya. The experiment comprised of ten genotypes of B. juncea viz.,Varuna, RKM 3, RK-08-02, Maya, SKM 0526, HUJM-05-03, RGN-229, RH-0512, LET-3, Purple mutant and Kranti (check). Crosses and parents were sown in Randomized Block Design with three replications under timely sown (E1), and late sown, (E2), with row to row and plant to plant distance of 30 and 10 cm, respectively. Normal agronomic procedures were used to raise the crop. This framework ensured adequate plant density and consistent crop management over the trial field, followed by meticulous thinning. Standard cultural practices for mustard cultivation were rigorously followed to ensure a healthy and competitive crop stand. The data were statistically analyzed separately for two environments and in pooled condition also.

S.N.	Parents	S.N.	Crosses	S.N.	Crosses
1	P1: Purple mutant	1	P1 x P2: Purple mutant x LET-3	24	P3 x P10: RH-0512 xVaruna
2	P2: LET-3	2	P1 x P3: Purple mutant x RH-0512	25	P4 x P5: RGN-229 x HUJM-05-03
3	P3: RH-0512	3	P1 x P4: Purple mutant x RGN-229	26	P4 x P6: RGN-229 x SKM 0526
4	P4: RGN-229	4	P1 x P5: Purple mutant x HUJM-05-03	27	P4 x P7: RGN-229 x Maya
5	P5: HUJM-05-03	5	P1 x P6: Purple mutant x SKM 0526	28	P4 x P8: RGN-229 x RK-08-02
6	P6: SKM 0526	6	P1 x P7: Purple mutant x Maya	29	P4 x P9: RGN-229 x RKM 3
7	P7: Maya	7	P1 x P8: Purple mutant x RK-08-02	30	P4 x P10: RGN-229 x Varuna
8	P8: RK-08-02	8	P1 x P9: Purple mutant x RKM 3	31	P5 x P6: HUJM-05-03x SKM 0526
9	P9: RKM 3	9	P1 x P10: Purple mutant x Varuna	32	P5 x P7: HUJM-05-03 x Maya
10	P10: Varuna	10	P2 x P3: LET-3 x RH-0512	33	P5 x P8: HUJM-05-03 x RK-08-02
		11	P2 x P4: LET-3 x RGN-229	34	P5 x P9: HUJM-05-03 x RKM 3
		12	P2 x P5: LET-3 x HUJM-05-03	35	P5 x P10: HUJM-05-03 x Varuna
		13	P2 x P6: LET-3 x SKM 0526	36	P6 x P7: SKM 0526 x Maya
		14	P2 x P7: LET-3 x Maya	37	P6 x P8: SKM 0526 x RK-08-02
		15	P2 x P8: LET-3 x RK-08-02	38	P6 x P9: SKM 0526 x RKM 3
		16	P2 x P9: LET-3 x RKM 3	39	P6 x P10: SKM 0526 x Varuna
		17	P2 x P10: LET-3 x Varuna	40	P7 x P8: Maya x RK-08-02

		18	P3 x P4: RH-0512 x RGN-229	41	P7 x P9: Maya x RKM 3
		19	P3 x P5: RH-0512 x HUJM-05-03	42	P7 x P10: Maya x Varuna
		20	P3 x P6: RH-0512 x SKM 0526	43	P8 x P9: RK-08-02 x RKM 3
		21	P3 x P7: RH-0512 x Maya	44	P8 x P10: RK-08-02 xVaruna
		22	P3 x P8: RH-0512 x RK-08-02	45	P9 x P10: RKM 3xVaruna
		23	P3 x P9: RH-0512 x RKM 3		

Yield traits

For each replication, five plants per genotype were chosen at random, and the subsequent observations were recorded.
Length of main raceme is the length of the main raceme, measured in centimeters.
Number of siliquae on main raceme is the number of siliquae on main raceme of the selected five plants at maturity, averaged.
Seeds per siliqua were recorded by taking ten siliquae from each chosen plant and noting down the average number of seeds per siliqua.
Thousand seed weight represents the weight of a thousand seeds randomly chosen from the overall yield of five plants of a genotype, measured in grams.
Seed yield per plant is determined by threshing, cleaning, and drying all siliquae from five selected plants per genotype. The resulting weight of the seeds is then recorded in grams.
Oil content (%) can be determined by the Soxhlet method14. Two grams of seeds from each treatment were crushed, and the oil was extracted with n-Hexane. The weight of the oil obtained from 100 g of seeds was recorded.
These observations provide comprehensive data for assessing the traits and attributes related to seed yield and quality.

Statistical analysis

The average values of genotypes within each replication were employed for statistical analysis. A randomised block design was used to assess the significance of variance between genotypes (treatments) for several attributes. The analysis of variance (ANOVA) was used to determine the importance of variation among genotypes (parents and F1s) across characteristics. The model included factors such as replication, treatments, and error to partition the variance. Mean sum of squares (MSS) values were calculated for each source of variation, including replications, genotypes (parents and hybrids), and the interaction between parents and hybrids (parents vs. F1s). The F-test was used to assess the significance of treatment effects, comparing the observed variance with expected values under the null hypothesis. Significant F-values revealed meaningful genotypic differences, enabling for additional investigation of genetic factors such as combining ability and heterosis.
Heterosis was initially proposed by Mather and Jinks, 2013. The calculation of heterosis, expressed as the percentage increase or decrease of F1 hybrids over the better parent by Fonseca and Patterson, 1968 and mid-parent suggested by Briggle, 1963, followed the formula below:
Heterosis (%) over better parent = (F1− Better parent)/ Better parent × 100
Heterosis (%) over mid parent = (F1− Mid parent)/ Mid parent × 100
where, F1 = mean value of F1

RESULTS

The effects of several crossings (combinations of parental genotypes, shown as P1, P2, etc.) on two traits—the number of siliquae on the main raceme and the length of the main raceme—as well as their pooled averages among habitats are shown in table 1a above. The mean performance (MP) and best parent performance (BP) for every cross are also included in the table. A moderate degree of statistical significance ($p < 0.05$) is indicated by the sign *, while a greater level of statistical significance ($p < 0.01$) is indicated by the sign **. Under the E environment, the cross P1 x P6 had a 25.89% increase in the number of siliquae compared to the mid parent, which was highly statistically significant (**). Under the E2 environment, the increase was 13.61%, which was also statistically significant.
This cross's pooled average likewise revealed a highly significant 20.22%. For the major raceme's trait length above the superior parent, another cross, P1 × P5, resulted in a -50.41% drop under environment 1, which was highly statistically significant. Significant decrease was noted in both environment 2 and the pooled condition, with values of -47.86% and -49.31%, respectively.
Data for seeds per siliquae and 1000-seed weight, two significant yield-related features, are shown in table 1b for two environments (E1 and E2) as well as other crosses with pooled data (combined across environments). Both mid-parent (MP) and better-parent (BP) heterosis are included in the statistics for this as well; they are shown as percentage deviations from mid-parent and better-parent values, respectively. Some crosses showed significant positive heterosis for the trait seeds per siliquae, meaning that hybrid vigour produced more seeds per siliquae than either parent. For example, Cross P1 × P9 showed mid-parent heterosis with values of +47.54% (in environment 1), +40.35% (in environment 2), and +44.07% (in pooled condition). With values of +32.35%, +37.93%, and +37.10%, this cross also demonstrated superior parent heterosis under environments 1, 2, and pooled conditions.
In all habitats and pooled data, this cross showed the highest positive heterosis, indicating the possibility of a substantial seed output. Mid-parent heterosis was demonstrated by the other cross, P6 × P9, with values of +36.36% (E1), +19.23% (E2), and +28.81% (pooled). improved parent heterosis with values of +22.58% (pooled), +32.35% (E1), and +10.71% (E2). Strong positive heterosis was also seen in this cross, especially in E1. Particularly in environment E2, where mid

parent heterosis was +45.45% (E2) and better parent heterosis was +29.03% (E2), the cross P5X P6 showed substantial positive heterosis. MP heterosis was 31.71% (E1), -10.71% (E2), and -23.19% (pooled), while BP heterosis was -44.00% (E1), -21.88% (E2), and -35.37% (pooled). These crossings were among the several that had considerable negative heterosis, which indicates fewer seeds per siliquae. Negative heterosis, which indicates incompatibility or reduced hybrid vigour, was consistently present in this cross.Cross P4 × P7 was another cross that had negative heterosis. It displayed BP Heterosis: -30.23% (E1), -46.51% (E2), -38.37% (pooled), and MP Heterosis values of -16.67% (E1), -31.34% (E2), and -23.74% (pooled). Significant decreases in seed quantities were also shown by this cross in both conditions.

The second trait highlighted in this table is the thousand-seed weight. The cross P2 × P3 exhibited positive heterosis with MP Heterosis of +14.83% (E1), +10.77% (E2), and +13.21% (pooled) under different environments, and BP Heterosis of +23.09% (E1), +15.18% (E2), and +16.87% (pooled). This cross consistently increased the 1000-seed weight, indicating its potential to enhance grain size and overall yield. The cross P3 × P9 showed moderate positive heterosis for seed weight, making it a potential candidate for improving seed size. However, negative heterosis was observed in some crosses for this trait, such as P1 × P4 and P6 × P9, which consistently reduced seed weight, indicating they may not be suitable for yield improvement.

The findings also show that these qualities are significantly impacted by the environment. The significance of environment-specific breeding techniques is demonstrated by the fact that certain crossings, such as P5 × P6 and P1 × P9, fared better in E2. Promising prospects for yield improvement initiatives, crosses like P1 × P9, P5 × P6, and P6 × P9 showed both increased seeds per siliquae and modest seed weight. P2 × P6 and P4 × P7, on the other hand, consistently displayed negative heterosis across both characteristics, indicating that these combinations might not be practical for increasing yield.

Table 1c presents the mid-parent (MP) and better-parent (BP) heterosis for seed yield per plant and oil content across two environments (E1 and E2), along with pooled data. Seed yield per plant is a critical factor in determining the success of hybrid breeding programs for mustard. Positive heterosis for a trait is desirable as it indicates increased productivity.

Table 1a: Estimates of heterosis (%) in a set of 10 x 10 diallel crosses of Indian mustard over E1, E2 environments and pooled

S. No.	Crosses	No. of siliquae on main raceme						Length of main raceme					
		MP			BP			MP			BP		
		E1	E2	Pooled	E1	E2	Pooled	E1	E2	Pooled	E1	E2	Pooled
	P1 × P2	-4.00	-6082	-5.24	-4.42	-16.33*	-9.52	-20.74**	25.77**	-3.02	-43.96**	19.58*	-24.01**
	P1 × P3	-5.68	-10.78	-7.95	-7.69	-16.33*	-9.52	31.25**	24.86**	28.31**	-4.77	-1.90	-3.50
	P1 × P4	-7.76	-15.58*	-11.20	-15.04**	-16.83*	-15.81*	65.30**	15.43*	42.60**	33.68**	5.95	21.92**
	P1 × P5	-12.90*	-29.47**	-20.44**	-20.59**	-33.03**	-26.12**	-27.79**	-29.97**	-28.78**	-50.41**	-47.86**	-49.31**
	P1 × P6	25.89**	13.61	20.22**	10.71	-2.04	4.76	42.26**	29.99**	36.49**	33.45**	83.84**	34.92**
	P1 × P7	-11.31*	-14.97	-12.89	-12.50	-27.55**	-19.52**	19.83*	8.40	14.60	10.30	0.57	13.34
	P1 × P8	11.92	-17.05*	-1.90	-3.57	-25.51**	-13.81	-12.96*	-13.47*	-13.18*	-35.25**	-27.18**	-31.90**
	P1 × P9	19.81**	-2.27	9.66	10.71	-12.24	0.00	-29.98**	-2.46	-18.47**	-50.16**	-16.93**	-37.69**
	P1 × P10	-27.34**	.25.53**	-26.61**	-39.16**	-28.57**	-33.20**	-30.31**	-23.48**	-27.16**	-50.44**	-41.42**	-46.45**
	P2 × P3	-20.87**	-5.99	-14.68*	-22.22**	-10.28	-17.17*	-31.94**	-13.13*	-24.77**	-34.75**	-29.04**	-28.95**
	P2 × P4	-4.07	8.38	1.18	-11.28*	-3.96	-8.12	-42.52**	-14.12*	-32.21**	-51.99**	-17.26*	-39.04**

	P2 × P5	-37.35**	-33.69**	-35.78**	-42.65**	-43.12**	-42.86**	-56.57**	-42.42**	-51.17**	-58.69**	-55.59**	-57.35**
	P2 × P6	-8.08	3.36	-3.17	-19.47**	-1.28	-12.04	-38.30**	3.41	-23.25**	-54.57**	-6.09	-39.35**
	P2 × P7	4.50	34.69**	16.53*	2.65	26.92**	12.57	44.30**	14.28	33.74	58.11**	24.09**	47.66**
	P2 × P8	6.19	-8.97	-0.57	-8.85	-8.97	-8.90	-44.82**	-28.46**	-38.84**	-48.99**	-37.11**	-38.94**
	P2 × P9	-13.46*	-7.69	-10.99	-20.35**	-7.69	-15.08	-54.01**	-25.52**	-44.16**	-54.54**	-33.70**	-46.05**
	P2 × P10	-24.01**	-15.48	-20.81**	-36.14**	-21.11*	-30.86**	-12.41**	-4.79	-9.48*	-13.26**	-24.35**	-17.21**
	P3 × P4	-12.80*	-9.00	-11.18	-18.05**	-15.84*	-17.09**	11.33*	-7.18	3.30	-3.66	-21.87**	-11.68*
	P3 × P5	-36.76**	-15.82*	-27.65**	-41.18**	-24.77**	-33.88**	-54.47**	-48.42**	-51.83**	-58.39**	-52.13**	-55.68**
	P3 × P6	8.91	5.85	7.57	-5.98	-3.29	-4.84	27.07**	17.07**	22.66**	-3.75	-11.19*	-7.03
	P3 × P7	-8.85	5.93	-2.84	-11.97	-4.45	-8.79	32.97**	34.63**	33.69**	2.16	0.21	1.30
	P3 × P8	62.63**	-10.88	29.35**	37.61**	-14.94	15.37	-6.62	-34.49**	-18.57**	-10.11**	-39.85**	-23.21**
	P3 × P9	17.92**	14.76	16.55*	6.87	9.53	4.98	-30.98**	-18.07**	-25.70**	-33.08**	-25.75**	-27.42**
	P3 × P10	-34.38**	-4.45	-16.74**	-35.54**	-6.67	-25.39**	-49.99**	-49.13**	-49.61**	-51.60**	-50.92**	-51.30**
	P4 × P5	17.47**	7.6	13.15*	16.18**	3.67	10.61	2.82	-7.25	-1.50	-17.49**	-26.49**	-21.38**
	P4 × P6	2.75	-10.42	-3.08	-15.79**	-23.76**	-19.23**	51.90**	-3.29	28.09**	29.48**	-15.05*	10.59
	P4 × P7	-1.45	-11.72	-5.81	-10.53	-25.70**	-17.08**	57.23**	0.34	33.26**	36.34**	-13.97	15.00*
	P4 × P8	-6.58	-26.26**	-15.52*	-24.81**	-34.65**	-29.06**	-16.03**	-24.02**	-19.38**	-24.86**	-30.96**	-27.39**
	P4 × P9	54.39**	29.61**	43.49**	32.33**	14.85	24.79**	13.45**	33.72**	21.48**	-4.35	23.12**	5.96
	P4 × P10	-49.83**	-30.89**	-42.45**	-54.82**	-34.65**	-44.92*	-46.60**	-36.94**	-42.40**	-55.05**	-48.43**	-52.12**
	P5 × P6	-4.07	-25.56**	-13.72*	-22.06**	-38.53**	-29.39**	-32.21**	-36.76**	-34.19**	-51.66**	-54.38**	-52.38**
	P5 × P7	-6.12	-10.11	-7.80	-15.44**	-26.61**	-20.41**	.22.69**	-23.38**	-22.98**	-44.18**	-45.66**	-44.82**
	P5 × P8	-17.05**	-19.79**	-18.32**	-33.82**	-31.19**	-32.65**	-50.91**	-46.07**	-48.75**	-56.666**	-53.73**	-55.39**

	P5 × P9	9.96	15.51*	12.44*	-6.62	-0.91	-4.08	-41.17**	-21.37**	-35.15**	-44.65**	-37.58**	-41.60**
	P5 × P10	-44.37**	-36.68**	-41.32**	-49.40**	-42.20**	-42.58**	-57.64**	-51.02**	-54.75**	-60.08**	-52.96**	-57.00**
	P6 × P7	-10.31	-10.00	-10.18	-20.18**	-11.27	-15.73	-7.63	-1.34	3.77	5.46	-4.08	3.72
	P6 × P8	21.69**	-8.72	7.30	18.82*	-12.82	6.29	-18.32**	-20.71**	-19.34**	-36.43**	-35.84**	-36.19**
	P6 × P9	4.44	-3.36	0.91	-1.05	-7.69	-4.05	-37.14**	-23.46**	-31.68**	-53.37**	-37.36**	-47.36**
	P6 × P10	-37.07**	-6.83	-22.82**	-49.40**	-16.67	-37.89**	-16.47**	-14.89	-15.77**	-38.11**	-36.98**	-37.61**
	P7 × P8	-12.63	-0.68	-7.42	-23.85**	-6.41	-12.36	10.62	34.97**	20.76**	-12.61*	6.91	-4.50
	P7 × P9	-12.759*	2.04	-6.55	-18.35**	-3.85	-7.87	-42.84**	-20.75**	-34.22**	-57.08**	-36.54**	-49.33**
	P7 × P10	-1.82	48.43**	16.59**	-18.67**	31.11**	-1.17	-11..60*	1.63	-5.86	-33.61**	-26.10**	-30.29**
	P8 × P9	7.95	-5.13	1.81	0.00	-5.13	-.2.31	-53.77**	-36.56**	-46.98**	-56.80**	-37.47**	-48.85**
	P8 × P10	-23.89**	-22.62**	-23.37**	-43.37**	-27.78**	-37.89**	-55.38**	-53.56**	-54.60**	-58.37**	-58.72**	-58.53**
	P9 × P10	-27.20**	-2.38	-17.48**	-42.77**	-8.89	-30.86**	-5.87	-15.76**	-9.93*	-6.05	-26.07**	-14.90**

BP= Better parent, MP= Mid parent

Note-*, ** significant at 5% & 1% probability levels, respectively. .P1: Purple mutant, P2: LET-3, P3: RH-0512, P4: RGN-229, P5: HUJM-05-03, P6: SKM 0526, P7: Maya, P8: RK-08-02, P9: RKM 3, P10: Varuna

Table 1b: Estimates of heterosis (%) in a set of 10 x 10 diallel crosses of Indian mustard over E_1, E_2 environments and pooled.

S. NO.	Crosses	Seed per siliquae						1000 seed weight					
		MP			BP			MP			BP		
		E1	E2	Pooled	E1	E2	Pooled	E1	E2	Pooled	E1	E2	Pooled
1	P1 × P2	-6.49	-1.64	-4.35	-28.00**	-6.25	-19.51**	-19.48**	26.84**	-2.49	-21.86**	25.72**	-4.64**
2	P1 × P3	17.65*	1.64	8.53	-2.44	-6.25	-4.11	-12.08**	0.64	-6.93**	-18.38**	-5.12*	-8.88**
3	P1 × P4	-11.43	-25.00**	-18.31**	-27.91**	-37.21**	-32.56**	-10.24**	9.69**	-2.61	-13.96**	9.29**	-5.01**
4	P1 × P5	-5.88	0.00	-3.13	-21.95**	-3.23	-13.89	-17.28**	-16.48**	-4.97**	-18.26**	11.46**	-7.20**
5	P1 × P6	8.47	-5.66	1.79	0.00	-13.79	1.79	-4.35**	1.01	-2.22	-15.08**	0.32	-9.35**

6	P1 × P7	3.57	9.43	6.42	0.00	0.00	3.57	-16.95**	-2.42	-11.56**	-18.32**	-4.52	-13.18**
7	P1 × P8	1.59	3.45	2.48	-11.11	3.45	-4.62	-13.66**	5.33*	-6.19**	-18.26**	1.87	-8.10**
8	P1 × P9	47.54**	40.35**	44.07**	32.35**	37.93**	37.10**	-12.08**	-9.46**	-11.05**	-16.82**	-12.32**	-12.95**
9	P1 × P10	1.64	7.41	2.61	11.76	0.00	0.00	-1.42	7.60**	2.05	-2.56*	1.40	-0.99
10	P2 × P3	27.47**	21.88**	25.16**	34.00**	21.88**	29.27**	14.83**	10.77**	13.21**	23.09**	15.18	16.87**
11	P2 × P4	-16.13**	-12.00	-14.29*	-22.00**	-23.26**	-16.28*	-12.90**	-0.10	-8.07**	-18*87**	-0.62	-12.87**
12	P2 × P5	7.69	-14.29	-10.39	-16.00**	-15.63	-15.85*	1.62	4.74	2.74	-2.52*	-0.62	-1.83
13	P2 × P6	-31.71**	-10.71	-23.19**	-44.00**	-21.88**	-35.37**	12.98**	7.24**	10.73**	-2.29	5.58*	0.56
14	P2 × P7	-31.65**	-10.71	-22.96**	-46.00**	-21.88**	-36.59**	2.27*	-5.32*	-1.51	-2.34	-8.146**	-4.45*
15	P2 × P8	-9.30	8.20	-2.04	-22.00**	3.12	-12.20	10.96**	-0.30	6.59**	2.11	-2.75	2.17
16	P2 × P9	-23.81**	-3.33	-15.28*	-36.00**	-9.38	-25.61**	-5.86**	-2.47	-4.55**	-13.42**	-4.73	-8.60**
17	P2 × P10	-16.67**	5.26	-7.80	-30.00**	-6.25	-20.73**	-14.54**	-6.31**	-11.42**	-16.12**	-10.98**	-12.14**
18	P3 × P4	-11.90*	-25.33**	-18.24**	-13.95*	-34.88**	-24.42**	14.79**	-0.30	8.51**	11.01**	-5.68*	8.08**
19	P3 × P5	-9.76	-20.63**	-14.48*	-9.76	-21.88**	-15.07**	-13.46**	-18.89**	-0.59	-18.76**	-7.54**	-0.86
20	P3 × P6	1.37	-3.57	-0.78	-9.76	-15.63	-12.33	.4.05**	5.96**	0.30	-8.58**	-0.74	-5.14**
21	P3 × P7	20.00**	-7.14	-7.94	2.44	-18.75*	-6.85	-11.92**	-29.03**	-18.84**	-16.95**	-34.45**	-19.05**
22	P3 × P8	-16.88**	-11.48	-14.49*	-21.95**	-15.63	-29.18*	-6.09**	-7.84**	-6.84**	-8.02**	-10.24**	-6.89**
23	P3 × P9	6.67	3.33	5.19	14.63*	9.38	12.33	13.00**	2.15	6.54**	10.75**	4.84	6.49**
24	P3 × P10	-4.00	-8.77	-6.06	-12.20	-18.75*	-15.07*	-5.24**	-7.31**	-6.10**	-12.96**	-7.35**	-10.74*
25	P4 × P5	21.43**	-10.81	6.33	18.60**	-23.26**	-2.33	-13.06**	16.91**	-1.81	-15.70**	11.48**	-1.93
26	P4 × P6	17.33**	1.49	9.86	2.33	-20.93**	-9.30	17.85**	-10.23**	6.31**	8.76**	-11.17**	0.91
27	P4 × P7	-16.67*	-31.34**	-23.74**	-30.23**	-46.51**	-38.37**	-8.53**	14.78**	0.37	-10.89**	11.90**	-0.28

28	P4 × P8	-8.86	-19.44**	-13.91*	-16.28*	-32.56**	-24.42**	-16.52**	-6.88**	-12.62**	-17.60**	-9.63**	-13.01**
29	P4 × P9	19.48**	-1.41	9.46	6.98	-18.60**	-5.81	-9.09**	11.40**	-0.80	-10.33**	8.28**	-1.14
30	P4 × P10	9.09	5.88	7.59	-2.33	-16.28**	-9.30	-14.99**	-5.16*	-11.11**	-19.42**	-10.33**	-15.82**
31	P5 × P6	23.29**	45.45**	32.81**	9.76	29.03**	18.06*	0.14	7.69**	3.10	-10.15**	3.73	-2.26
32	P5 × P7	25.71**	23.64**	24.80**	7.32	9.68	8.33	-11.02**	8.94**	-7.59**	-17.42**	6.48*	-8.08**
33	P5 × P8	9.09	20.00**	13.87*	2.44	16.13	8.33	-13.70**	15.21**	-2.54	-17.36**	6.78**	-2.85
34	P5 × P9	-4.00	5.08	-4.48	-12.20	-9.68	-11.11	-9.44**	17.30**	0.88	-13.34**	8.87**	0.65
35	P5 × P10	-17.33**	-3.57	-11.45	-24.39**	-12.90	-19.44*	8.7**	-3.29	4.11**	6.09**	-12.56**	-1.29
36	P6 × P7	21.31**	37.50**	28.44**	15.62*	37.50**	25.00*	-6.47**	1.41	-3.34	-15.72**	-0.11	-8.81**
37	P6 × P8	5.88	28.30**	15.70*	0.00	17.24	7.69	-2.43	5.11*	0.76	-8.86**	0.98	-4.77*
38	P6 × P9	36.36*	19.23*	28.81**	32.35**	10.71	22.58*	-5.49**	-24.42**	-13.48**	-11.66**	-27.29**	-18.14**
39	P6 × P10	--3.03	-22.45*	-11.30	-5.88	-24.00*	-13.56	Table 1c: Estimates of heterosis (%) in a			-10.10**	-10.33**	-10.19**
40	P7 × P8	20.00**	13.21	16.95*	8.33	3.45	6.15	-3.88**	9.65**	1.42	-7.54**	3.83	1.22
41	P7 × P9	11.11	34.62**	21.74**	2.94	25.00**	12.90	-13.47**	-45.73*_	-10.04**	-16.82**	-9.66**	-10.32**
42	P7 × P10	14.29	18.37	16.07	5.88	16.00	10.17	-3.91**	-3.68	-3.82*	-6.57**	-11.07**	-835**
43	P8 × P9	-22.86**	-8.77	-16.54*	-25.00**	-10.34	-18.46*	14.24**	-1.13	7.86**	14.16**	-1.28	7.75**
44	P8 × P10	0.00	-3.70	-1.61	-2.789	-10.34	-6.15	-12.06**	-8.36**	-10.56**	-17.65**	-10.79**	-14.94**
45	P9 × P10	20.59**	47.17**	32.23**	20.59**	39.29**	29.03**	5.17**	0.00	3.08*	-1.58	-2.79	-2.06

BP= Better parent, MP= Mid parent
Note-*, ** significant at 5% & 1% probability levels, respectively.
P1: Purple mutant, P2: LET-3, P3: RH-0512, P4: RGN-229, P5: HUJM-05-03, P6: SKM 0526, P7: Maya, P8: RK-08-02, P9: RKM 3, P10: Varuna

Table 1c: Estimates of heterosis (%) in a set of 10 × 10 diallel crosses of Indian mustard over E1, E2 environments and pooled.

S. No.	Crosses	Seed yield per plant						Oil content					
		MP			BP			MP			BP		
		E1	E2	Pooled	E1	E2	Pooled	E1	E2	Pooled	E1	E2	Pooled
1	P1 × P2	-41.10**	-29.75**	-37.20**	-42.85**	-35.15**	-40.11	2.46**	0.80	1.67	2.06*	0.00	1.04
2	P1 × P3	-16.65	-18.39*	-17.27	-39.56**	-33.25**	-37.47**	-3.81**	-6.22**	-5.00**	-4.85**	-7.45**	-6.13**
3	P1 × P4	-51.28**	-31.37**	-45.52**	-51.31**	-43.70**	-48.79**	-3.71	-3.20	-3.46	-4.71	-3.24	-3.95
4	P1 × P5	-19.90**	-29.44**	-23.22**	-28.00*	-31.77**	-29.25**	4.83**	5.89**	5.35**	2.35*	3.46**	2.90**
5	P1 × P6	-23.39**	-25.19**	-24.02**	-41.28**	-37.70**	-40.10**	0.90	3.88**	2.36*	-0.32	2.32*	0.98
6	P1 × P7	-23.50**	-38.54**	-28.82**	-26.95**	-41.58**	-29.68**	-1.16	2.68**	0.73	-2.91**	1.02	-0.98
7	P1 × P8	-12.32	-31.49**	-19.52**	-28.00**	-31.77**	-29.25**	-1.20	-4.62**	-2.88**	-2.59*	-5.90**	-4.22**
8	P1 × P9	-52.49**	-41.77**	-48.76**	-57.00**	-43.25**	-52.44**	0.86	0.15	0.50	-0.46	-0.89	-0.67
9	P1 × P10	-0.56	-5.86	-2.45	-20.52**	-29.08**	-23.68**	-1.26	-1.90*	-1.58	-1.81	-2.16	-1.98
10	P2 × P3	-42.40**	-43.24**	-42.71**	-56.00**	-56.35**	-58.06**	-1.49	-2.57**	-2.02*	-2.17*	-3.08**	-2.62*
11	P2 × P4	11.06	4.84	9.17	13.74*	26.63**	18.32*	0.22	0.63	0.42	1.20	0.13	0.67
12	P2 × P5	-46.70**	-48.24**	-47.26**	-53.35**	-53.67**	-53.47**	0.04	1.31	0.67	-2.69**	-1.78	-2.24*
13	P2 × P6	41.30**	-36.72**	12.85	6.07	-50.54**	-14.04**	2.24*	6.54**	4.35**	0.61	4.12**	2.35*
14	P2 × P7	-451.10**	-54.29**	-45.92**	-45.35**	-55.68**	-49.02*	3.25**	0.51	1.90*	1.81	-0.33	0.76
15	P2 × P8	-41.82**	-49.48**	-44.79**	-53.33**	-53.54**	-53.41**	-3.69**	-4.12**	-3.90**	-5.41**	-6.14**	-5.77**
16	P2 × P9	19.68**	-19.26**	5.45	-27.20**	-6.15	1.46	-0.21	0.63	-0.23	-2.23	-2.02	-1.11
17	P2 × P10	-36.41**	-36.79**	-36.55**	-47.97**	-49.46**	-48.52**	-1.04	3.51**	1.20	-1.21	2.95**	1.01
18	P3 × P4	-11.14	2.34	-7.04	-35.54**	1.94	-26.50**	-1.63	-2.21	-1.92*	-3.69**	-3.45**	-3.57**

19	P3 × P5	-4.92	-29.86**	-14.49	-25.63**	-41.05**	-31.29**	-1.71	-2.00*	-1.85*	-5.04**	-5.47**	-5.25**
20	P3 × P6	26.90*	48.39*	35.42*	17.06	45.07**	27.77*	2.51**	2.11*	2.31*	0.20	-0.72	-0.25
21	P3 × P7	-29.44**	-15.26	-23.92**	-47.25**	-33.36**	-42.02**	-3.77**	-2.87**	-3.33**	-4.46**	-3.18**	-3.83**
22	P3 × P8	6.08	10.92	8.163	9.78	8.98	9.11	0.27	2.87**	1.55	2.72**	5.41**	4.04**
23	P3 × P9	-8.68	-1.45	-5.90	-28.97**	-17.73*	-24.84**	2.38**	3.48**	2.92**	-0.01*	1.09	0.53
24	P3 × P10	-32.67**	-35.99**	-33.93**	-57.69**	-57.42**	-57.42**	0.38	0.91	0.64	-0.15	-0.16	-0.15
25	P4 × P5	-39.14**	-20.92*	-33.62**	-45.26**	-33.33**	-35.02**	6.35**	0.41	3.41**	4.91**	-1.93	1.51
26	P4 × P6	-28.29**	36.28**	-9.11	-45.02**	33.73**	-24.77**	5.24**	2.31*	3.79**	5.05**	0.74	2.91**
27	P4 × P7	-37.18**	12.91	-21.52**	-39.98**	-10.95	-25.37**	1.29	-1.44	-0.06	-1.52	-3.00**	-2.25*
28	P4 × P8	-30.70**	-37.86**	-33.07**	-43.07**	-48.86**	-37.71**	2.73**	1.1	1.98*	2.34*	-0.18	1.89
29	P4 × P9	-39.78**	10.96	-24.38**	-45.47**	-7.07	-25.40**	0.98	2.33*	1.64	0.72	1.23	0.97
30	P4 × P10	-58.45**	-53.95**	-56.98**	-66.80**	-69.50**	-67.80**	3.38**	0.07	1.75	1.75	-0.15	0.82
31	P5 × P6	33.37**	-14.74	15.41	11.23	-26.99**	-2.80	3.31**	4.41**	3.85**	2.09*	3.55**	2.81**
32	P5 × P7	2.50	-12.33	-3.03	-3.80	-19.28*	-9.64	-0.08	0.67	0.29	-4.13**	-3.19**	-3.67**
33	P5 × P8	7.73	8.80	8.15	-2.77	5.63	2.72	1.50	3.26**	2.37*	0.51	0.25*	1.36
34	P5 × P9	2.07*	-12.36	8.15	19.14*	-13.08	7.30	3.06**	1.72	2.40*	1.92	0.41	1.17
35	P5 × P10	-60.43**	-55.33**	-58.55**	-70.77**	-67.09**	-69.41**	-2.15*	-1.45	-1.81	-4.98**	-3.95**	-4.47**
36	P6 × P7	8.27	16.81*	11.51	-14.15	-6.56	-11.29	0.42	-4.85**	-2.17**	-2.53*	-7.77**	-5.10**
37	P6 × P8	30.54**	-10.11	13.82	19.42	-24.89**	0.21	2.01*	-1.05	0.51	1.80	-1.20	0.48
38	P6 × P9	5.14	-10.51	-0.71	-12.86	-23.89**	-16.91	1.49	-1.39	0.08	1.41	-1.85	-0.12
39	P6 × P10	-48.00**	-48.44**	-48.17**	-65.71**	-65.53**	-65.64**	-1.69	0.21	-0.76	-3.41**	-1.54	-2.50*
40	P7 × P8	-26.33**	-22.72**	-24.88**	-37.16**	-26.83**	-33.26**	0.37	-5.47**	-2.50**	-2.77**	-8.22**	-5.45**

41	P7 × P9	-10.47	2.02	-6.57	-15.36	-7.21	-12.29	-3.98**	-5.04**	-4.50**	-6.87**	-7.52**	-7.19**
42	P7 × P10	-29.00**	-34.50**	-31.05**	-45.17**	-48.83**	-46.53**	-4.43**	-2.25*	-3.36**	-5.61**	-3.58**	-4.61**
43	P8 × P9	-28.15**	9.14	-13.29	-35.60**	6.81	-18.27*	2.71**	0.86	1.80	2.58*	0.55	1.58
44	P8 × P10	-31.31**	28.12**	-8.22	-52.45**	-3.75	-34.47**	1.58	-3.13**	-0.74	-4.40	-4.6**	-2.50
45	P9 × P10	-48.16**	-54.48**	-50.49**	-61.51**	-66.29**	-63.27**	2.01*	0.88	1.45	0.15	-0.42	-0.13

BP= Better parent, MP= Mid parent

Note-*, ** significant at 5% & 1% probability levels, respectively.

P1: Purple mutant, P2: LET-3, P3: RH-0512, P4: RGN-229, P5: HUJM-05-03, P6: SKM 0526, P7: Maya, P8: RK-08-02, P9: RKM 3, P10: Varuna

The cross P2 × P6 exhibited positive heterosis with MP heterosis values of +41.30% (E1) and +12.85% (pooled), and BP heterosis values of +6.07% (E1), though negative in pooled data (-14.04%). This cross showed the highest MP heterosis for seed yield in E1, indicating its potential as a high-yielding hybrid, especially under favorable conditions. The cross P3 × P6, with MP heterosis values of +26.90% (E1) and +35.42% (pooled), and BP heterosis values of +17.06% (E1) and +27.77% (pooled), demonstrated consistent significant positive heterosis across environments, indicating a stable and high-yielding hybrid. Another cross, P6 × P8, showed potential in E1, but its performance was inconsistent in E2, indicating possible environmental sensitivity.

Several crosses demonstrated significantly negative heterosis for seed yield, suggesting reduced seed yield compared to their parents. For instance, P1 × P9 exhibited MP heterosis values of -52.49% (E1) and -48.76% (pooled), and BP heterosis values of -57.00% (E1) and -52.44% (pooled). This cross consistently showed reduced yield, making it unsuitable for yield improvement. The cross P4 × P10 exhibited MP heterosis values of -58.45% (E1) and -56.98% (pooled), and BP heterosis values of -66.80% (E1) and -67.80% (pooled). This cross exhibited one of the most significant yield reductions, suggesting genetic incompatibility.

The next trait studied was oil content, which is essential for economic value, particularly in mustard. Positive heterosis is desirable to enhance oil yield. The study indicated that the cross P1 × P5, with MP heterosis values of +4.83% (E1) and +5.35% (pooled), and BP heterosis values of +2.35% (E1) and +2.90% (pooled), exhibited significant positive heterosis for oil content across environments, making it a promising candidate for oilseed breeding. The cross P2 × P6 showed MP heterosis values of +2.24% (E1) and +4.35% (pooled), and BP heterosis values of +0.61% (E1) and +2.35% (pooled). This cross showed consistent positive heterosis under E1, highlighting its potential for improving oil content. The cross P3 × P8 demonstrated significant heterosis, particularly in E2, making it an environment-specific hybrid for oil content improvement.

Negative heterosis was observed in the cross P1 × P3 under E1 and pooled conditions, indicating that this cross is not suitable for breeding programs aimed at oil improvement. Another cross that showed negative heterosis was P7 × P8, with MP heterosis values of -5.47% (E2) and -2.50% (pooled), and BP heterosis values of -2.77% (E1) and -5.45% (pooled). This cross showed reduced oil content across environments, making it a less desirable combination.

Overall, the results indicated that crosses P2 × P6 and P3 × P6 exhibited significant positive heterosis for both seed yield and oil content, making them ideal candidates for breeding programs aimed at dual trait improvement. Crosses P6 × P8 and P3 × P8 also showed promise, though their performance may be environment-specific. Several crosses exhibited varying performance across environments (e.g., P6 × P8), highlighting the need for location-specific hybrid evaluation to identify stable and adaptable hybrids. Crosses such as P1 × P9 and P4 × P10 consistently showed negative heterosis for both traits, indicating genetic incompatibility or lack of hybrid vigor. These combinations should be avoided in future breeding programs.

The table 2 presents the heterosis (hybrid vigor) exhibited by different crosses across various traits in two environments (E1, E2) and pooled conditions. Heterosis which is measured as a percentage increase over the mid-parent (MP) and better parent (BP) values for each cross and higher the values indicate the possible combination for improving the trait.

Table 2. Crosses exhibiting the highest heterosis over mid-parent and better parent in E1, E2 environments and pooled.

Character	MP			BP		
	E1	E2	Pooled	E1	E2	Pooled

Length of main raceme	P1 × P4 (65.30 %)	P7 × P8 (34.97%)	P1 × P4 (42.60%)	P4 × P7 (36.34%)	P1 × P6 (23.84%)	P1 × P6 (34.92%)
Number of siliquae on main raceme	P3 × P8 (62.63%)	P7 × P10 (48.43%)	P4 × P9 (43.49%)	P3 × P8 (37.61%)	P7 × P10 (31.11%)	P4 × P9 (24.79%)
Seeds\ siliqua	P1 × P9 (47.54%)	P9 × P10 (47.17%)	P1 × P9 (44.07%)	P1 × P9 (37.95%)	P9 × P10 (39.29%)	P1 × P9 (37.29%)
1000- seed weight	P4 × P6 (17.85%)	P1 × P2 (26.84%)	P2 × P6 (10.73%)	P8 × P9 (14.16%)	P1 × P2 (25.72%)	P3 × P4 (8.08%)
Seed yield per plant	P2 × P6 (41.30%)	P3 × P6 (48.39%)	P2 × P6 (35.42%)	P6 × P8 (19.42%)	P3 × P6 (45.07%)	P3 × P6 (27.77%)
Oil content	P3 × P6 (5.24%)	P2 × P6 (6.54%)	P1 × P5 (5.35%)	P4 × P6 (5.05%)	P2 × P6 (4.12%)	P4 × P6 (2.91%)

WhereP1: Purple mutant, P2: LET-3, P3: RH-0512, P4: RGN-229, P5: HUJM-05-03, P6: SKM 0526, P7: Maya, P8: RK-08-02, P9: RKM 3, P10: Varuna

The trait length of main raceme influences the overall plant architecture and yield potential and is considered as an important trait for brassica. In this experiment under environment 1, cross P1 × P4 exhibited the highest MP heterosis (65.30%), indicating a significant improvement over the average of the two parents and under environment 2 P7 × P8 showed the highest heterosis (34.97%). While taking the pooled data cross P1 × P4 again had the highest heterosis (42.60%), suggesting its consistent performance across environments. Cross P4 × P7 showed the highest improvement (36.34%) over the better parent under E1 and P1 × P6 demonstrated the best performance with 23.84% and 34.92% heterosis, in E2 and pooled condition respectively.

The number of siliquae directly impacts seed yield per plant. The table indicated under E1 P3 × P8 exhibited the highest mid parent heterosis (62.63%), under E2 cross P7 × P10 (48.43%) and in pooled condition cross P4 × P9 (43.49%). The better parent heterosis under E1 was highest in cross P3 × P8 also with 37.61% while in E2 cross P7 × P10 (31.11%) and under pooled cross P4 × P9 (24.79%). Seeds per Siliqua, a critical trait for determining total seed output showed highest MP Heterosis under E1 and pooled condition for P1 × P9 (47.54% and 44.07%, respectively) while in E2 cross P9 × P10 (47.17%) showed highest MP. Under E1 and pooled condition P1 × P9 maintained the highest BP heterosis (37.95% and 37.29%, respectively) and cross P9 × P10 (39.29%) depicted highest BP under E2.

The trait thousand seed weight often correlates with better marketability and productivity of crops. In E1, highest MP was observed in P4 × P6 (17.85%) and in E2 P1 × P2 (26.84%), showing substantial improvement. The better parent heterosis was observed to have highest for P8 × P9 (14.16%) in E1, for P1 × P2 (25.72%) in E2 and for P3 × P4 (8.08%) under pooled data.

Similarly seed Yield Per Plant is the most important trait for evaluating overall productivity. The mid parent heterosis under E1, E2 and pooled data was highest in crosses P2 × P6 (41.30%), P3 × P6 (48.39%) and P2 × P6 (35.42%). The better parent heterosis was highest in P6 × P8 (19.42%) under E1 and under E2 & Pooled cross P3 × P6 showed consistently high performance (45.07% and 27.77%, respectively).

For the trait oil content which is a crucial economic trait in mustard, mid parent heterosis cross P3 × P6 exhibited a modest improvement (5.24%) in E1 and in E2 cross P2 × P6 (6.54%) performed the best while under Pooled condition crossP1 × P5 (5.35%). Better parent heterosis was highest in cross P4 × P6 (5.05%) in E1 and P2 × P6 (4.12%) in E2 and P4 × P6 (2.91%) under pooled condition.

The cross P1 × P4 (for length of main raceme) and P2 × P6 (for seed yield per plant) performed consistently across environments and pooled conditions and cross P4 × P9 performed well for the number of siliquae across all conditions. The results indicates that some crosses, such as P7 × P8 for raceme length and P9 × P10 for seeds per siliqua, showed better performance in one specific environment (E2) compared to others. Certain crosses like P3 × P6 exhibited good heterosis for seed yield, they may not have performed equally well for other traits like 1000-seed weight or oil content, indicating potential trade-offs. Pooled data gives a more balanced picture of performance across environments. Crosses like P1 × P9, P4 × P9, and P2 × P6 emerged as reliable performers in the pooled analysis.

The results conclude that crosses P2 × P6, P3 × P6, and P1 × P9 showed strong heterosis for key yield-related traits across environments, making them promising candidates for breeding programs focused on improving yield and oil content. Environmental effects should also be considered when selecting crosses for specific regions.

The table 3 provides the number of desirable crosses for different traits in terms of relative heterosis (MP) and heterobeltiosis (BP) across two environments (E1, E2) and pooled conditions. For the trait number of Siliquae on Main Raceme under E1, seven crosses showed significant improvement over the mid-parent and under E2, only 3 crosses were desirable, indicating a lower heterosis expression in this environment. When Heterobeltiosis (BP) was observed, under E1, 4 crosses outperformed the better parent and under E2 and Pooled, only 2 crosses were desirable, suggesting that surpassing the better parent is more challenging and environmentally sensitive. For Length of Main Raceme under E1, 11 crosses exhibited positive MP heterosis, indicating good hybrid performance in this environment and under E2, 8 crosses were desirable. Based on Heterobeltiosis (BP), for this trait under E1, 5 crosses performed better than the better parent and under E2 and Pooled, 4 crosses consistently showed improvement, reflecting moderate stability.

Table3: The number of desirable crosses for relative heterosis (MP) and heterobeltiosis (BP) in E1, E2 environment and pooled.

Character	MP			BP		
	E1	E2	Pooled	E1	E2	Pooled
Number of siliquae on main raceme	7	3	8	4	2	2
Length of main raceme	11	8	9	5	4	4
Seeds / Siliquae	13	10	11	6	7	6
1000 seed weight	10	10	9	6	12	4
Seed Yield / Plant	6	4	1	4	3	2
Oil Content	15	12	11	8	6	5

The analysis of heterosis across various traits revealed distinct patterns in their performance under different environments (E1, E2) and pooled conditions. For seeds per siliqua, a key yield component, 13 crosses exhibited positive relative heterosis (MP) in E1, demonstrating high heterotic potential, while 10 crosses were desirable in E2. Across pooled environments, 11 crosses maintained favorable performance, suggesting moderate stability. In terms of heterobeltiosis (BP), 6 and 7 crosses outperformed the better parent in E1 and E2, respectively, with 6 crosses showing consistent improvement across pooled conditions. Similarly, 1000-seed weight, an important trait for yield and market value, showed 10 desirable crosses with positive relative heterosis in both E1 and E2, indicating environmental stability, though pooled conditions supported only 9 crosses. However, heterobeltiosis was more variable, with 6 crosses surpassing the better parent in E1, 12 in E2, and only 4 demonstrating consistent improvement across pooled environments, highlighting environmental influence. For seed yield per plant, a critical economic trait, only 6 crosses exhibited positive relative heterosis in E1, decreasing to 4 in E2, with just 1 cross showing stability in pooled conditions, indicating high sensitivity to environmental variation. Heterobeltiosis was similarly limited, with only 4 and 3 crosses surpassing the better parent in E1 and E2, respectively, and 2 crosses maintaining stability across environments. In contrast, oil content, a vital quality trait in oilseed crops, demonstrated a robust response to hybridization, with 15 crosses showing positive relative heterosis in E1, 12 in E2, and 11 maintaining performance across pooled environments. Heterobeltiosis for oil content was lower, with 8 crosses in E1, 6 in E2, and 5 displaying stable improvement across environments. Overall, environmental influence played a significant role, with most traits exhibiting superior performance in E1 compared to E2, highlighting the variability of heterosis expression. Traits like oil content and seeds per siliqua showed greater stability across environments, making them promising candidates for breeding programs. The pooled performance indicated a general reduction in the number of desirable crosses, reflecting the challenge of achieving consistent performance under varying conditions. Additionally, the number of crosses demonstrating relative heterosis was consistently higher than those showing heterobeltiosis, as surpassing the mid-parent is typically more attainable than surpassing the better parent. Notably, traits such as 1000-seed weight and oil content exhibited significant heterosis over the better parent, underscoring their potential for genetic improvement in breeding programs.

DISCUSSION

The study of heterosis in Brassica species, particularly Brassica juncea, has advanced understanding of the genetic and molecular mechanisms underpinning hybrid vigor (Aakanksha et al., 2021). This research emphasizes the importance of heterosis in enhancing yield-related traits such as seed yield, oil content, seeds per siliquae, and 1000-seed weight, which are critical for the economic value of mustard crops. The observed mid-parent (MP) and better-parent (BP) heterosis values highlight the potential of specific crosses to improve these traits under varying environmental conditions (Patelet al., 2012).

The cross P1 × P6 demonstrated significant heterosis, with MP values of +25.89% (E1) and +13.61% (E2) (table 1a), and a pooled average of +20.22%. This enhancement, statistically significant at $p< 0.01$, indicates a strong hybrid vigour for this yield-related trait, consistent with earlier studies on Brassica. Conversely, P1 × P5 showed a substantial decrease in raceme length, with MP heterosis values of -50.41% (E1), -47.86% (E2), and -49.31% (pooled), indicating potential genetic incompatibility or deleterious alleles.The cross P2 × P6 exhibited the highest MP heterosis for seed yield (+41.30% in E1), suggesting its suitability for high-yielding hybrid programs. Similar stability was observed for P3 × P6 across environments. Positive heterosis for oil content was demonstrated by crosses such as P1 × P5 and P2 × P6, indicating their potential for improving oil yield (Wolko et al., 2019).

Negative heterosis in crosses like P1 × P9 and P4 × P10 for seed yield and in P1 × P4 for oil content suggests that these combinations may involve deleterious genetic interactions. These findings align with prior research emphasizing the need for targeted selection of favourable allele combinations to optimize productivity.

Crosses P1 × P9 and P6 × P9 showed strong positive heterosis for seeds per siliquae, with pooled MP values of +44.07% and +28.81%, respectively. Conversely, P5 × P6 and P4 × P7 exhibited negative heterosis, highlighting genetic incompatibility. For 1000-seed weight, P2 × P3 demonstrated consistent positive heterosis, with pooled MP and BP values of +13.21% and +16.87%, respectively. These findings reinforce the potential of specific crosses to enhance seed size and yield.

Significant environmental interactions were observed, with traits like siliquae number and oil content showing differential performance across environments (E1 and E2). For example, P5 × P6 and P1 × P9 performed better in E2, underscoring

the importance of environment-specific hybrid evaluation. The study has similarity with the results observed by Saroj et al. (2021) and Diana et al. (2013).
Traits like oil content and seeds per siliquae exhibited greater stability across environments, making them reliable targets for breeding programs (Ahmed et al., 2021). In contrast, seed yield and raceme length displayed high environmental sensitivity, necessitating location-specific breeding strategies (Saroj et al., 2021).
The data underscore the importance of integrating genetic insights with environmental adaptability in Brassica breeding programs. Crosses such as P2 × P6, P3 × P6, and P1 × P9, which showed strong heterosis for key traits, emerge as promising candidates for improving yield and oil content. Conversely, crosses exhibiting consistent negative heterosis, such as P1 × P5, are less suitable for breeding programs.
Advanced techniques like marker-assisted selection and quantitative trait loci (QTL) mapping can further enhance the identification and development of high-performing hybrids. Future research should focus on elucidating the molecular mechanisms driving heterosis and optimizing breeding strategies to maximize its benefits (Akhatar et al., 2022).

CONCLUSION
The study shows that there are promising potential for selecting progenies with higher seed yield and associated characteristics in Indian mustard.The study highlights the significant role of heterosis in enhancing yield-related traits in Brassica juncea. Crosses Purple mutant x RKM 3 and SKM 0526 x RKM 3 showed strong positive heterosis for seeds per siliquae, with pooled MP values of +44.07% and +28.81%, respectively. Conversely, HUJM-05-03 x SKM 0526RGN-229 x Maya exhibited negative heterosis, highlighting genetic incompatibility. For 1000-seed weight, LET-3 x RH-0512 demonstrated consistent positive heterosis, with pooled MP and BP values of +13.21% and +16.87%, respectively. These findings reinforce the potential of specific crosses to enhance seed size and yield. Crosses such as LET-3 x SKM 0526, RH-0512 x SKM 0526 and Purple mutant x RKM 3, which showed strong heterosis for key traits, emerge as promising candidates for improving yield and oil content. Conversely, crosses exhibiting consistent negative heterosis, such as P1 × P5, are less suitable for breeding programs. Specific crosses demonstrated strong potential for improving traits like seed yield, oil content, and siliquae number. However, the observed environmental effects underscore the need for tailored breeding strategies to develop hybrids adapted to specific conditions. Advanced genetic tools and a deeper understanding of heterosis mechanisms will be pivotal in maximizing the productivity and economic value of mustard crops.

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Ethical issues: None

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