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GENETIC COMPONENTS, COMBINING ABILITY, AND HETEROSIS ANALYSIS FOR YIELD AND RELATED TRAITS IN INDIAN MUSTARD (*Brassica juncea* L.)

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ABSTRACT

The present study was conducted to estimate genetic makeup, combining ability and heterosis for yield and allied characters in Indian mustard [*Brassica juncea* (L.) Czern. & Coss.] through the half diallel mating methodology. Seven diverse parents, viz., NRCDR-2, Rohini, Maya, Azad Mahak, Vaibhav, PR-20 and Basanti, along with their twenty-one F_1 hybrids were evaluated for twelve quantitative characters during Rabi season of 2023-24 at Oilseed Research Farm, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh. Genetic component analysis revealed significant additive (D) and dominance (H_1 and H_2) variance components for most of the traits, indicating the importance of both gene actions in the inheritance of these characters. The degree of dominance was found to be more than one in case of several quantitative traits such as plant height, length of the main raceme, secondary branches, seeds per silique, oil content and seed yield per plant indicating the predominance of overdominance gene action. Analysis of combining ability also indicated significant general combining ability (GCA) and specific combining ability (SCA) effects for all traits, reflecting the importance of both additive and non-additive gene effects on hybrid performance. SCA variance exceeded GCA variance for most traits, indicating the predominance of non-additive gene action. From the set of parental varieties, NRCDR-2, Azad Mahak and PR-20 were considered good general combining ability varieties for seed yield and associated characteristics. Hybrids such as NRCDR-2 x PR-20 and NRCDR-2 x Azad Mahak showed high SCA effects and heterosis for seed yield per plant whereas hybrids such as Maya x Basanti and Azad Mahak x PR-20 were outstanding for oil content. These findings indicate that the identified parents and hybrids could be effectively utilized in future mustard improvement programmes.

Key words: *Brassica juncea*, Diallel analysis, Combining ability, Heterosis, Seed yield

Introduction

The Indian mustard (*Brassica juncea* (L.) Czern. & Coss.) is one of the most important oilseed crops grown in India and several other Asian countries. It plays a significant role in the production of edible oils owing to the fact that it can easily adapt to diverse environments. The oil content of the seeds is quite high – 38-45%, along with approximately 25-30% proteins (Meena *et al.*, 2015; Pradhan and Pental, 2011). Despite remarkable success in developing crop varieties and implementing certain farming practices, the productivity of the plant still falls

short of its true potential. Breeding programmes aim to genetic improve seed yield and oil content in mustard. The success of a breeding program is largely determined by finding genetically superior parents and knowledge of the genetic basis of economically significant characters. Knowledge of additive and non-additive gene action facilitates the identification of suitable breeding strategies. Hence, investigations on combining ability and heterosis are important for the selection of suitable parents and hybrids. (Falconer & Mackay, 1996; Mather & Jinks, 1982).

Table 1: Description of parental genotypes used in the study.

S. No.	Parents	Pedigree	Characters
1	NRCDR-2	ICAR-DRMR	Days to maturity: 130-135 days, Oil content: 36.5-42.5 %
2	ROHINI	CSAUA&T, KANPUR	Days to maturity: 125- 130 days, Oil content: 41-43 %
3	MAYA	CSAUA&T, KANPUR	Days to maturity: 130-135 days, Oil content: 39-40 %
4	AZAD MAHAK	MATHURA RAI X JD-6	Days to maturity: 130-33 days, Oil content: 41.6-42.6 %
5	VAIBHAV	CSAUA&T, KANPUR	Days to maturity: 120-125 days, Oil content: 36-38 %
6	PR-20	Pure line selection from KRANTI	Days to maturity: 130-135 days, Oil content: 38.8-39.5 %
7	BASANTI	CSAUA&T, KANPUR	Days to maturity: 130-132 days, Oil content: 40-42%

Diallel mating designs have been widely used in crop improvement programs to estimate the genetic components of variability and assess the breeding potential of parental lines. The study of combining ability helps in assessing general combining ability (GCA), which is primarily associated with additive gene effects whereas specific combining ability (SCA) is mainly governed by dominance and epistatic gene effects. The ratio of GCA to SCA variance is helpful in determining the pattern of inheritance of the trait and choosing the appropriate breeding method (Hayman, 1954; Griffing, 1956). Heterosis or hybrid vigour is another important genetic effect that has been widely employed in crop improvement to enhance productivity. The detection of hybrids that perform better than their parent lines and standard check varieties allow breeders to select high-yielding varieties and offers an opportunity to exploit non-additive gene action. Various scientists have found heterosis and combining ability effects on yield and its

Table 2: List of cross combinations.

S. No.	CROSS COMBINATIONS
1.	NRCDR-2 X ROHINI
2.	NRCDR-2 X MAYA
3.	NRCDR-2 X AZAD MAHAK
4.	NRCDR-2 X VAIBHAV
5.	NRCDR-2 X PR-20
6.	NRCDR-2 X BASANTI
7.	ROHINI X MAYA
8.	ROHINI X AZAD MAHAK
9.	ROHINI X VAIBHAV
10.	ROHINI X PR-20
11.	ROHINI X BASANTI
12.	MAYA X AZAD MAHAK
13.	MAYA X VAIBHAV
14.	MAYA X PR-20
15.	MAYA X BASANTI
16.	AZAD MAHAK X VAIBHAV
17.	AZAD MAHAK X PR-20
18.	AZAD MAHAK X BASANTI
19.	VAIBHAV X PR-20
20.	VAIBHAV X BASANTI
21.	PR-20 X BASANTI

contributing factors in Indian mustard, thereby indicating the possibility of enhancing productivity using hybrid breeding methods (Sharma *et al.*, 2017; Chaurasiya *et al.*, 2018; Mandal *et al.*, 2023; Chauhan *et al.*, 2024).

Although much information is available on the combining ability and heterosis in Indian mustard, the expression of these genetic effects depends on the combinations of parents and environmental factors. Therefore, the present investigation was undertaken to estimate genetic components, combining ability and heterosis for yield and related traits using a half diallel mating design in Indian mustard.

Materials and Methods

The experiment was conducted at the Oilseed Research Farm, Chandra Shekhar Azad University of Agriculture and Technology, Kalyanpur, Kanpur, Uttar Pradesh, India, during Rabi 2022-23 and 2023-24. Seven different mustard varieties, that is, NRCDR-2, Rohini, Maya, Azad Mahak, Vaibhav, PR-20 and Basanti, were mated through half-diallel crosses without reciprocals during Rabi 2022-23 to produce twenty-one F_1 hybrids. The hybrids along with their parents and a standard check variety (Azad Mahak) were assessed during Rabi 2023-24 using Randomized Block Design (RBD) with three replications. Each genotype was grown in a single 5.0-meter-long row with 45 cm inter-row spacing and 20 cm between plants, adjusted through thinning 15 days after sowing to ensure uniform stand density. Data on twelve quantitative characters including days to 50% flowering, days to maturity, plant height, length of main raceme, number of primary branches per plant, number of secondary branches per plant, siliquae on main raceme, total siliquae per plant, number of seeds per siliquae, 1000-seed weight, oil content and seed yield per plant observations were recorded on five randomly selected competitive plants.

Analysis of variance (ANOVA) was conducted as per the methodology of Panse and Sukhatme (1967) to assess the significance of genotypic differences. Combining ability analysis was performed according to Griffing's Method II, Model I (1956). Estimation of

Table 3: Estimates of variance components analysis and related parameters for 12 traits in Indian mustard.

Com.	DF	DM	LMR	PH	SMR	PBP	SBP	TSP	NSS	SW	OC	SYP
D	0.32	2.33**	5.63	43.60**	51.11**	3.53**	2.52*	1539.14*	0.763**	0.336**	0.795**	0.449
SE±	0.68	0.70	3.99	7.43	9.57	1.06	0.94	702.37	0.238	0.057	0.080	0.250
F	0.81	3.94*	-9.50	-21.99	27.57	2.38	4.18	663.95	-0.098	-0.126	-0.555*	0.175
SE±	1.64	1.68	9.58	17.82	22.95	2.54	2.26	1684.96	0.571	0.137	0.191	0.599
H ₁	9.15**	7.47**	91.51**	92.21**	94.20**	11.91**	16.54**	5599.58**	3.782**	0.544**	1.012**	3.636**
SE±	1.64	1.68	9.62	17.88	23.03	2.55	2.27	1690.93	0.573	0.137	0.191	0.601
H ₂	8.12**	4.76**	82.21**	74.42**	66.07**	10.10**	12.41**	5148.95**	3.659**	0.513**	0.878**	3.508**
SE±	1.45	1.48	8.47	15.76	20.30	2.25	2.00	1489.94	0.505	0.121	0.169	0.530
h ₂	7.91**	0.31	149.80**	57.63**	34.90*	2.47	0.96	4932.94**	8.165**	0.621**	2.125**	8.369**
SE±	0.97	1.00	5.69	10.58	13.63	1.51	1.34	1000.71	0.339	0.081	0.113	0.356
E	0.52*	0.47	2.33	3.58	1.92	0.33	0.48	91.36	0.125	0.012	0.024	0.351**
SE±	0.24	0.25	1.41	2.63	3.38	0.38	0.33	248.32	0.084	0.020	0.028	0.088
(H ₁ /D) ^{1/2}	5.33	1.79	4.03	1.45	1.36	1.84	2.56	1.91	2.23	1.27	1.13	2.84
H ₂ /4H ₁	0.22	0.16	0.22	0.20	0.18	0.21	0.19	0.23	0.24	0.24	0.22	0.24
((4D/H ₁) ^{1/2} +F)/((4DH ₁) ^{1/2} -F)	1.61	2.79	0.65	0.70	1.50	1.45	1.96	1.25	0.94	0.74	0.53	1.15
h ₂ /H ₂	0.97	0.07	1.82	0.77	0.53	0.24	0.08	0.96	2.23	1.21	2.42	2.39
h ₂	9.71	24.84	34.80	65.27	58.35	34.16	25.68	32.47	32.14	63.79	75.26	14.09
R	-0.466	0.627	0.101	-0.069	-0.223	0.028	-0.263	-0.193	-0.408	-0.226	-0.351	-0.722

Com: Components; DF: Days to 50% flowering; DM: Days to maturity; LMR: Length of main raceme (cm); PH: Plant height (cm); SMR: Siliquae on main raceme; PBP: Primary branches per plant; SBP: Secondary branches per plant; TSP: Total siliquae per plant; NSS: No. of seeds per siliquae; SW: 1000 seed weight (g); OC: Oil content %; SYP: Seed Yield per plant (g)
Values marked with * and ** indicate significance at the 5% ($P \leq 0.05$) and 1% ($P \leq 0.01$) levels, respectively

genetic components and analysis of combining ability were done as per methodology suggested by Hayman (1954) and Griffing (1956), respectively. Estimates of heterosis were made based on mid-parent, better parent and standard parent (Azad Mahak).

Results

Genetic Components of Variation

The genetic variance component estimates for twelve quantitative traits in Indian mustard are given in Table 3.

The variance components for additive genes (D) and dominance (H₁ and H₂) were found to be significant for most of the traits, reflecting the role of both additive and non-additive gene actions in inheritance of these traits. However, the value of dominance variance was more in comparison to the additive variance for most traits, reflecting that the non-additive gene actions have greater predominance. The mean degree of dominance [(H₁/D)^{1/2}] was found to exceed unity for all traits studied,

Table 4: Analysis of variance of combining ability and their ratios for 12 traits in Indian mustard.

SV		DF	DM	LMR	PH	SMR	PBP	SBP	TSP	NSS	SW	OC	SYP
gca	6	1.09**	2.39**	43.62**	163.36**	106.41**	6.47**	4.33**	2981.33**	2.148**	1.027**	2.964**	1.133**
sca	21	2.75**	1.78**	28.44**	24.82**	22.06**	3.01**	3.88**	1571.64**	1.301**	0.161**	0.326**	1.406**
Error	54	0.54	0.48	1.67	3.54	1.90	0.32	0.49	91.21	0.128	0.011	0.016	0.353
Var due to gca		0.06	0.21	4.66	17.76	11.61	0.68	0.43	321.12	0.224	0.113	0.328	0.087
Var due to sca		2.21	1.30	26.77	21.29	20.16	2.69	3.39	1480.43	1.172	0.150	0.309	1.053
Gca/sca Ratio		0.03	0.16	0.17	0.83	0.58	0.25	0.13	0.217	0.19	0.75	1.06	0.08

SV: Source of Variation; DF: Days to 50% flowering; DM: Days to maturity; LMR: Length of main raceme (cm); PH: Plant height (cm); SMR: Siliquae on main raceme; PBP: Primary branches per plant; SBP: Secondary branches per plant; TSP: Total siliquae per plant; NSS: No. of seeds per siliquae; SW: 1000 seed weight (g); OC: Oil content %; SYP: Seed Yield per plant (g) Values marked with * and ** indicate significance at the 5% ($P \leq 0.05$) and 1% ($P \leq 0.01$) levels, respectively

Table 5: Estimates of general combining ability (GCA) effects of seven parents for twelve quantitative traits in Indian mustard.

S.	Pa/Hy	DF	DM	LMR	PH	SMR	PBP	SBP	TSP	NSS	SW	OC	SYP
1	NRCDR-2	-0.54*	-0.34	1.48**	2.26**	-0.33	0.07	-0.02	16.75**	0.47**	0.19**	-0.13**	0.46*
2	ROHINI	0.46*	0.55*	0.99*	3.56**	-0.08	-0.01	-0.02	12.35**	0.09	-0.23**	0.27**	-0.35
3	MAYA	-0.17	-0.08	1.20**	2.93**	2.46**	1.16**	1.30**	2.85	-0.06	0.27**	0.06	0.18
4	AZAD MAHAK	0.13	-0.63**	0.87*	0.81	4.28**	0.39*	0.07	13.74**	0.42**	0.26**	0.57**	0.25
5	VAIBHAV	-0.24	0.25	-1.39**	-8.94**	-6.68**	-0.75**	-0.39	-27.56**	-0.93**	-0.65**	-0.67**	-0.37*
6	PR-20	0.02	-0.45*	-4.48**	-1.25*	-0.75	-1.40**	-1.02**	-23.79**	0.29*	0.17**	-0.80**	0.22
7	BASANTI	0.35	0.70**	1.32**	0.62	1.12*	0.53**	0.07	5.66	-0.28*	0.00	0.68**	-0.38*
	gca(j)	0.227	0.214	0.399	0.580	0.426	0.175	0.216	2.947	0.111	0.033	0.039	0.183
	se gi-gj	0.347	0.327	0.609	0.887	0.650	0.267	0.330	4.502	0.169	0.050	0.060	0.280

Pa/Hy: Parent/Hybrids; DF: Days to 50% flowering; DM: Days to maturity; LMR: Length of main raceme (cm); PH: Plant height (cm); SMR: Siliquae on main raceme; PBP: Primary branches per plant; SBP: Secondary branches per plant; TSP: Total siliquae per plant; NSS: No. of seeds per siliquae; SW: 1000 seed weight (g); OC: Oil content %; SYP: Seed Yield per plant (g) Values marked with * and ** indicate significance at the 5% ($P \leq 0.05$) and 1% ($P \leq 0.01$) levels, respectively

Table 6: Estimates of general combining ability (GCA) effects of seven parents for twelve quantitative traits in Indian mustard.

S.	Hy	DF	DM	LMR	PH	SMR	PBP	SBP	TSP	NSS	SW	OC	SYP
1	A	-0.86**	-1.51**	3.64**	1.89*	4.99**	1.03**	1.25**	15.79**	1.32**	0.85**	0.12*	0.71**
2	B	0.10	0.12	4.29**	4.05**	5.31**	1.26**	1.19**	31.68**	0.15	0.31**	0.00	0.85**
3	C	-1.53**	-0.99**	3.83**	3.77**	4.29**	1.36**	2.82**	16.07**	0.73**	0.27**	0.53**	1.12**
4	D	-0.82**	1.12**	-5.25**	-6.41**	0.12	-0.63**	-1.92**	-12.50**	0.21	-0.46**	0.35**	0.14
5	E	-1.08**	-1.51**	8.57**	7.84**	3.72**	3.95**	2.91**	71.73**	0.93**	0.47**	-0.35**	1.75**
6	F	-1.42**	-0.66*	-0.03	-0.44	0.99	-0.91**	-1.51**	2.74	-1.11**	-0.24**	0.66**	-0.78**
7	G	1.44**	0.23	0.59	-2.58**	-2.67**	0.47*	1.59**	-30.12**	-0.14	-0.28**	-0.03	-0.61*
8	H	-0.86**	-0.21	3.25**	8.67**	-3.82**	1.91**	-1.71**	22.07**	0.11	-0.31**	0.47**	0.06
9	I	0.84**	-2.10**	2.78**	3.96**	1.87**	0.45	0.08	-0.04	1.12**	0.16**	0.21**	1.28**
10	J	-0.42	-0.40	-1.00	-3.39**	-1.73**	-0.90**	-0.75**	13.06**	-0.02	-0.03	-0.25**	0.69**
11	K	-1.08**	0.12	1.67**	2.93**	5.74**	-1.70**	-2.30**	27.14**	0.61**	0.16**	0.34**	0.56*
12	L	-0.90**	1.42**	4.17**	4.84**	2.50**	-0.06	-0.50	-15.04**	1.53**	0.26**	0.43**	-0.20
13	M	-3.53**	0.19	0.70	3.45**	0.00	-0.06	2.09**	103.66**	0.88**	0.07	0.02	1.22**
14	N	1.21**	1.23**	-3.88**	-0.10	1.73**	-2.07**	-1.48**	2.56	0.46**	0.28**	0.10	-0.77**
15	O	0.88**	-0.92**	4.98**	4.23**	-9.80**	1.86**	2.17**	-12.96**	-1.04**	0.05	0.95**	1.50**
16	P	0.18	1.75**	-3.30**	3.30**	-1.82**	-1.02**	-0.88**	-40.62**	-0.74**	0.54**	-0.38**	0.82**
17	Q	-2.08**	-1.21**	-3.08**	-1.64*	4.51**	-1.30**	-0.92**	-7.13	0.38*	-0.02	0.79**	-0.90**
18	R	0.92**	0.64*	3.98**	-5.92**	2.84**	-2.03**	-2.26**	41.69**	0.55**	-0.16**	0.04	0.16
19	S	2.29**	-1.10**	3.24**	-3.23**	0.01	-0.29	0.41	12.70**	0.20	-0.18**	0.30**	0.65**
20	T	-0.05	1.75**	8.98**	-0.50	-3.66**	2.77**	2.93**	-2.15	0.83**	0.19**	-0.01	-0.42
21	U	-1.97**	-0.21	-0.50	-1.12	3.21**	0.89**	0.16	-24.25**	1.81**	0.50**	0.17**	1.13**
	sca(ii)	0.660	0.623	1.160	1.688	1.238	0.508	0.629	8.572	0.321	0.095	0.114	0.533
	sca(ij)	0.300	0.283	0.527	0.768	0.563	0.231	0.286	3.899	0.146	0.043	0.052	0.243
	se(sij-ik)	0.981	0.925	1.723	2.508	1.840	0.755	0.935	12.734	0.477	0.141	0.169	0.792

A: NRCDR-2 × ROHINI; B: NRCDR-2 × MAYA; C: NRCDR-2 × AZAD MAHAK; D: NRCDR-2 × VAIBHAV; E: NRCDR-2 × PR-20; F: NRCDR-2 × BASANTI; G: ROHINI × MAYA; H: ROHINI × AZAD MAHAK; I: ROHINI × VAIBHAV; J: ROHINI × PR-20; K: ROHINI × BASANTI; L: MAYA × AZAD MAHAK; M: MAYA × VAIBHAV; N: MAYA × PR-20; O: MAYA × BASANTI; P: AZAD MAHAK × VAIBHAV; Q: AZAD MAHAK × PR-20; R: AZADMAHAK × BASANTI; S: VAIBHAV × PR-20; T: VAIBHAV × BASANTI; U: PR-20 × BASANTI

Hy: Hybrids; DF: Days to 50% flowering; DM: Days to maturity; LMR: Length of main raceme (cm); PH: Plant height (cm); SMR: Siliquae on main raceme; PBP: Primary branches per plant; SBP: Secondary branches per plant; TSP: Total siliquae per plant; NSS: No. of seeds per siliquae; SW: 1000 seed weight (g); OC: Oil content %; SYP: Seed Yield per plant (g) Values marked with * and ** indicate significance at the 5% ($P \leq 0.05$) and 1% ($P \leq 0.01$) levels, respectively

Table 7A: Estimates of heterosis over MP, BP, and SP for seed yield.

S.	Hy	Days to 50 flowering			Days to maturity			Length of main raceme (cm)			Plant height (cm)		
		BP	MP	EP	BP	MP	EP	BP	MP	EP	BP	MP	EP
1	A	-4.06*	-3.82**	-5.03**	-3.18**	-2.46**	0.51	11.53**	12.25**	10.47**	3.37*	3.98**	6.94**
2	B	-3.55*	-2.31	-4.52**	-0.99	-0.13	1.27	11.94**	12.98**	11.50**	5.43**	5.50**	7.79**
3	C	-6.53**	-6.06**	-6.53**	-2.23**	-1.13	0.00	10.55**	11.79**	10.55**	4.13**	5.29**	6.47**
4	D	-5.08**	-3.86**	-6.03**	0.00	0.50	2.28**	-0.73	0.37	-2.93	-6.61**	-2.04	-4.52**
5	E	-5.08**	-4.59**	-6.03**	-2.48**	-2.36**	-0.25	12.33**	16.63**	9.83**	5.21**	5.46**	7.57**
6	F	-5.56**	-5.32**	-6.03**	-0.99	-0.99	1.27	8.92**	10.49**	6.50**	0.43	1.09	4.04**
7	G	0.51	1.55	-1.01	-1.71*	-0.12	2.03**	6.93**	7.23**	6.50**	1.35	2.02	4.85**
8	H	-4.02*	-3.29*	-4.02*	-2.44**	-0.62	1.27	9.28**	9.80**	9.28**	6.21**	8.02**	9.88**
9	I	-0.51	0.52	-2.01	-3.18**	-1.98**	0.51	7.05**	8.92**	6.03**	-1.49	3.91**	1.91
10	J	-2.04	-1.79	-3.52*	-2.44**	-1.60*	1.27	-1.20	3.22	-2.14	-1.31	-0.50	2.09
11	K	-3.54*	-3.05*	-4.02*	-1.22	-0.49	2.54**	8.97**	11.24**	7.93**	2.91*	2.98*	6.61**
12	L	-5.03**	-3.32*	-5.03**	1.52*	1.77**	2.03**	10.63**	10.85**	10.63**	5.22**	6.31**	7.42**
13	M	-6.25**	-6.25**	-9.55**	0.50	0.88	1.78*	4.22	6.34**	3.81	-0.79	4.00**	1.29
14	N	0.00	0.78	-2.01	0.00	0.75	2.03**	-4.94*	-0.42	-5.31*	1.44	1.60	3.56*
15	O	-1.52	0.00	-2.01	-0.99	-0.13	1.27	12.58**	15.24**	12.13**	3.26*	4.02**	6.98**
16	P	-3.52*	-1.79	-3.52*	1.25	1.89**	2.54**	-1.35	0.85	-1.35	0.04	3.83**	0.04
17	Q	-6.53**	-5.58**	-6.53**	-2.24**	-1.26	-0.25	-4.76*	-0.04	-4.76*	-0.22	0.66	1.54
18	R	-1.51	-1.26	-1.51	-0.25	0.88	2.03**	10.55**	13.38**	10.55**	-3.26*	-1.55	0.22
19	S	1.54	2.33	-0.50	-1.49*	-1.12	0.51	4.64*	7.50**	0.08	-6.35**	-1.98	-4.70**
20	T	-3.03	-1.54	-3.52*	1.24	1.75**	3.55**	18.99**	19.38**	13.80**	-5.57**	-0.32	-2.17
21	U	-5.56**	-4.83**	-6.03**	-0.74	-0.62	1.52*	4.05	6.54**	-1.15	-1.81	-0.93	1.73
	SE ±	1.04	0.90		0.98	0.85		1.83	1.58		2.66	2.30	
	CD at 5 %	2.09	1.81		1.97	1.71		3.68	3.18		5.35	4.63	
	CD at 1 %	2.86	2.47		2.69	2.33		5.02	4.34		7.30	6.32	
A: NRCDR-2 × ROHINI; B: NRCDR-2 × MAYA; C: NRCDR-2 × AZAD MAHAK; D: NRCDR-2 × VAIBHAV; E: NRCDR-2 × PR-20; F: NRCDR-2 × BASANTI; G: ROHINI × MAYA; H: ROHINI × AZAD MAHAK; I: ROHINI × VAIBHAV; J: ROHINI × PR-20; K: ROHINI × BASANTI; L: MAYA × AZAD MAHAK; M: MAYA × VAIBHAV; N: MAYA × PR-20; O: MAYA × BASANTI; P: AZAD MAHAK × VAIBHAV; Q: AZAD MAHAK × PR-20; R: AZADMAHAK × BASANTI; S: VAIBHAV × PR-20; T: VAIBHAV × BASANTI; U: PR-20 × BASANTI													
Values marked with * and ** indicate significance at the 5% ($P \leq 0.05$) and 1% ($P \leq 0.01$) levels, respectively													

reflecting over dominance. Moreover, the ratio of $H_2/4H_1$ for all traits was less than 0.25.

Analysis of combining ability

The ANOVA results for combining ability are provided in Table 4. It is evident that the mean squares for general combining ability (GCA) and specific combining ability (SCA) for all the traits under study were highly significant which indicates the contribution of both additive and non-additive gene effects. However, variance for SCA was more than variance for GCA for most of the traits which indicates predominance of non-additive gene effects. Greater values of GCA/SCA ratios have been obtained for oil content, plant height and 1000-seed weight which indicate comparatively higher additive gene effects for these traits.

The GCA effect estimates (Table 5) revealed a wide variation among the parents. NRCDR-2 was having significant positive GCA effects for total siliquae per plant, seeds per siliqua and seed yield per plant. Azad Mahak was found to be a good general combiner for oil content, siliquae on the main raceme and seed yield whereas Maya was a good general combiner for primary and secondary branches per plant. Basanti was found to be a good general combiner for oil content, while PR-20 was having favourable GCA effects for seed yield and other related traits. The SCA effect estimates (Table 6) also showed variations among the hybrids. The hybrid NRCDR-2 × PR-20 had highly significant positive SCA effects for seed yield and various yield contributing traits followed by NRCDR-2 × Azad Mahak. For oil content, the hybrids Maya × Basanti and Azad Mahak × PR-20 had favourable

Table 7B: Estimates of heterosis over MP, BP, and SP for seed yield.

S.	Hy	Siliquae of main raceme			Primary branches per plant			Secondary branches per plant			Total siliquae per plant		
		BP	MP	EP	BP	MP	EP	BP	MP	EP	BP	MP	EP
1	A	9.15**	15.23**	0.32	16.88*	31.15**	-2.17	1.54	9.85*	-2.95	8.92**	12.32**	5.05
2	B	1.26	12.39**	3.80	6.91	30.31**	9.24	11.54*	18.57**	2.65	17.32**	17.95**	6.30*
3	C	4.77*	15.00**	4.77*	3.80	25.45**	3.80	4.42	15.31**	4.42	5.38*	10.57**	5.38*
4	D	5.11	6.10*	-13.58**	9.09	14.06	-21.74**	-1.08	-0.36	-18.58**	1.28	7.82**	-8.24**
5	E	13.91**	16.48**	-2.02	68.46**	69.17**	10.33	21.94**	22.60**	0.00	20.20**	27.42**	8.91**
6	F	-0.99	7.63**	-3.07	-8.09	8.35	-13.59*	-9.40*	-2.69	-14.75**	6.12*	8.84**	1.21
7	G	-7.89**	-2.87	-5.58*	0.00	9.94	2.17	9.26*	11.32**	4.42	-3.17	0.38	-6.60*
8	H	-4.77*	-0.76	-4.77*	7.61	17.16**	7.61	-15.63**	-13.73**	-15.63**	5.69*	7.60**	5.69*
9	I	-3.34	2.95	-11.16**	3.25	11.19	-13.59*	-5.56	1.49	-9.73*	-3.23	6.02*	-6.66*
10	J	-0.26	3.04	-8.33**	-16.23*	-5.67	-29.89**	-12.35**	-5.65	-16.22**	0.18	9.30**	-3.38
11	K	5.20*	8.52**	2.99	-15.61*	-10.70	-20.65**	-14.51**	-13.84**	-18.29**	8.97**	9.58**	5.11
12	L	3.39	4.67*	5.98*	-1.06	0.00	1.09	-4.42	-0.46	-4.42	-3.39	1.88	-3.39
13	M	-12.54**	-2.12	-10.35**	-10.11	5.63	-8.15	14.10**	20.47**	5.01	24.59**	31.98**	11.69**
14	N	-3.47	4.97*	-1.05	-31.38**	-16.10*	-29.89**	-6.09	-0.68	-13.57**	3.43	9.10**	-7.28**
15	O	-14.91**	-12.95**	-12.77**	15.43*	20.22**	17.93**	14.11**	15.37**	7.37	0.07	3.17	-4.56
16	P	-10.35**	-0.76	-10.35**	-22.28**	-9.49	-22.28**	-13.57**	-5.18	-13.57**	-14.30**	-4.58	-14.30**
17	Q	4.53	12.39**	4.53	-29.89**	-14.99*	-29.89**	-16.52**	-8.27	-16.52**	-7.04**	3.09	-7.04**
18	R	4.77*	5.88**	4.77*	-20.11**	-17.65**	-20.11**	-17.70**	-15.20**	-17.70**	8.21**	10.77**	8.21**
19	S	-0.28	2.91	-14.23**	-3.79	0.99	-30.98**	6.09	6.28	-12.68**	10.49**	11.00**	-11.23**
20	T	-14.62**	-6.38**	-16.41**	16.76*	32.46**	9.78	9.72*	17.06**	3.24	-3.94	4.71	-8.38**
21	U	1.24	7.78**	-0.89	-5.20	12.14	-10.87	-6.27	0.17	-11.80**	-7.68**	0.21	-11.95**
	SE ±	1.95	1.69		0.80	0.69		0.99	0.86		13.51	11.70	
	CD at 5 %	3.93	3.40		1.61	1.39		1.99	1.73		27.18	23.53	
	CD at 1 %	5.36	4.64		2.20	1.90		2.72	2.36		37.08	32.11	
A: NRCDR-2 × ROHINI; B: NRCDR-2 × MAYA; C: NRCDR-2 × AZAD MAHAK; D: NRCDR-2 × VAIBHAV; E: NRCDR-2 × PR-20; F: NRCDR-2 × BASANTI; G: ROHINI × MAYA; H: ROHINI × AZAD MAHAK; I: ROHINI × VAIBHAV; J: ROHINI × PR-20; K: ROHINI × BASANTI; L: MAYA × AZAD MAHAK; M: MAYA × VAIBHAV; N: MAYA × PR-20; O: MAYA × BASANTI; P: AZAD MAHAK × VAIBHAV; Q: AZAD MAHAK × PR-20; R: AZADMAHAK × BASANTI; S: VAIBHAV × PR-20; T: VAIBHAV × BASANTI; U: PR-20 × BASANTI													
Values marked with * and ** indicate significance at the 5% ($P \leq 0.05$) and 1% ($P \leq 0.01$) levels, respectively													

SCA effects.

Heterosis for yield and associated traits

Estimates of heterosis for mid-parent, better parent, and standard parent are given in Table 7. Significant positive heterosis for seed yield per plant was recorded in the crosses NRCDR-2 × PR-20 and NRCDR-2 × Azad Mahak, which show that the crosses performed better than the standard parent. Maya × Basanti recorded good heterosis for oil percentage as well as other yield traits, while PR-20 × Basanti showed good heterosis for seeds per siliqua and 1000-seed weight.

Discussion

The predominance of dominance variance over additive variance indicates that non-additive gene effects played a major role in the inheritance of most yield and

yield-related traits in the present investigation. The over-dominance observed for several characters suggests that hybridization could be an effective breeding approach for improving seed yield and associated traits in Indian mustard. The unequal distribution of positive and negative alleles among parents further indicates sufficient genetic diversity available for exploitation through suitable breeding strategies. Similar findings have also been reported by Sharma *et al.*, (2017), Chaurasiya *et al.*, (2018) and Chauhan *et al.*, (2024), who also reported the predominance of non-additive gene action for important economic traits in Indian mustard.

In this respect, the concurrent importance of GCA and SCA variances implied the inclusion of additive as well as non-additive genetic effects in the regulation of the investigated traits. Nonetheless, the higher importance

Table 7C: Estimates of heterosis over MP, BP, and SP for seed yield.

S.	Hy	No. of seeds per siliquae			1000 seed weight (g)			Oil content (%)			Seed yield per plant (g)		
		BP	MP	EP	BP	MP	EP	BP	MP	EP	BP	MP	EP
1	A	16.49**	22.01**	19.02**	21.74**	28.97**	11.51**	0.36	1.64**	0.15	10.42*	13.94**	4.76
2	B	5.85	9.64**	8.15	11.24**	15.83**	10.67**	1.34**	1.72**	-0.68	12.12*	13.19**	8.42
3	C	14.36**	15.59**	16.85**	9.63**	14.44**	9.63**	1.85**	3.26**	1.85**	10.26*	13.16**	10.26*
4	D	-0.53	12.65**	1.63	-14.89**	-1.87	-22.04**	1.16*	2.01**	-1.59**	6.95	12.15**	1.47
5	E	14.89**	20.33**	17.39**	20.87**	21.54**	11.96**	-0.90*	0.44	-3.60**	18.77**	19.23**	13.55**
6	F	-5.85	-1.12	-3.80	3.46	3.90	-5.24	2.26**	3.76**	2.45**	1.54	4.16	-3.66
7	G	8.00	9.25*	2.72	-8.64**	0.54	-9.11**	0.45	1.35**	0.23	-0.76	3.35	-4.03
8	H	8.70*	12.68**	8.70*	-9.89**	-0.61	-9.89**	2.68**	2.79**	2.68**	0.00	5.81	0.00
9	I	14.04**	23.81**	5.98	0.40	9.87**	-18.36**	-0.73	1.36**	-0.95*	16.05**	17.99**	3.30
10	J	14.62**	14.62**	6.52	1.40	7.99**	-6.08*	-2.18**	0.38	-2.39**	8.05	11.90**	3.30
11	K	15.20**	15.54**	7.07	3.84	9.58**	-5.69	2.46**	2.67**	2.65**	10.16*	10.84*	-0.73
12	L	19.02**	22.01**	19.02**	10.92**	11.21**	10.92**	2.08**	3.11**	2.08**	1.47	3.17	1.47
13	M	8.00	18.50**	2.72	-9.94**	7.44*	-10.41**	0.08	1.29**	-1.91**	9.47*	15.83**	5.86
14	N	14.86**	16.18**	9.24*	10.20**	14.13**	9.63**	-0.05	1.67**	-2.04**	1.52	2.10	-1.83
15	O	-2.86	-1.45	-7.61	2.34	7.00**	1.81	3.42**	4.56**	3.61**	10.98*	14.90**	7.33
16	P	-6.52	4.88	-6.52	-1.42	17.85**	-1.42	-1.65**	0.53	-1.65**	4.03	11.81**	4.03
17	Q	12.50**	16.62**	12.50**	3.62	7.58**	3.62	0.87*	3.62**	0.87*	-2.20	0.00	-2.20
18	R	9.24*	13.56**	9.24*	-2.39	2.30	-2.39	2.44**	2.54**	2.63**	0.37	5.59	0.37
19	S	7.60	16.83**	0.00	-10.54**	3.64	-17.13**	1.06*	1.57**	-3.33**	7.66	13.31**	2.93
20	T	8.82	17.83**	0.54	-4.48	9.73**	-13.25**	-0.68	1.62**	-0.49	4.07	6.44	-6.23
21	U	27.49**	27.86**	18.48**	17.31**	18.46**	8.66**	-0.55	2.26**	-0.36	10.34*	13.61**	5.49
	SE ±	0.51	0.44		0.15	0.13		0.18	0.16		0.84	0.73	
	CD at 5 %	1.02	0.88		0.30	0.26		0.36	0.31		1.69	1.46	
	CD at 1 %	1.39	1.20		0.41	0.36		0.49	0.43		2.31	2.00	

A: NRCDR-2 × ROHINI; B: NRCDR-2 × MAYA; C: NRCDR-2 × AZAD MAHAK; D: NRCDR-2 × VAIBHAV;
E: NRCDR-2 × PR-20; F: NRCDR-2 × BASANTI; G: ROHINI × MAYA; H: ROHINI × AZAD MAHAK; I: ROHINI × VAIBHAV;
J: ROHINI × PR-20; K: ROHINI × BASANTI; L: MAYA × AZAD MAHAK; M: MAYA × VAIBHAV; N: MAYA × PR-20;
O: MAYA × BASANTI; P: AZAD MAHAK × VAIBHAV; Q: AZAD MAHAK × PR-20; R: AZADMAHAK × BASANTI;
S: VAIBHAV × PR-20; T: VAIBHAV × BASANTI; U: PR-20 × BASANTI

Values marked with * and ** indicate significance at the 5% ($P \leq 0.05$) and 1% ($P \leq 0.01$) levels, respectively

of SCA variance in respect of majority of the traits underlined the greater contribution of dominant and epistatic genetic effects compared to additive genetic effects. In this regard, the better general combiners obtained in the current research such as NRCDR-2, Azad Mahak and PR-20 may prove to be useful parents in future breeding programs. Likewise, the hybrids having high SCA effects would prove helpful for making use of heterosis and selection of superior segregants in coming generations.

The presence of high heterosis along with substantial SCA effects in superior hybrids indicates that there is a predominance of non-additive gene effect in seed yield and associated characters. These hybrids provide an opportunity to obtain the desired genetic stock to develop high yielding lines of mustard through hybridization

followed by selection programs. Heterosis and recurrent and pedigree selection could help improve the genetics of Indian mustard. Similar findings have been reported by Sharma *et al.*, (2017), Mandal *et al.*, (2023) and Chauhan *et al.*, (2024).

Conclusion

The above study demonstrated the presence of large amounts of genetic variability amongst the parental genotypes and hybrids for twelve quantitative characters in Indian mustard. Additive as well as non-additive genetic effects were found to contribute in the inheritance of the traits studied, but the dominance variance being higher than additive variance, higher SCA variance than GCA variance and occurrence of over-dominance in majority of the traits highlighted the importance of non-additive genetic effects in determining the expression of the

characters, especially seed yield and its components. In case of parental genotypes, NRCDR-2, Azad Mahak and PR-20 were observed to be better general combiners for seed yield and its allied characters. As far as hybrids were concerned, NRCDR-2 × PR-20 and NRCDR-2 × Azad Mahak hybrids showed high SCA effects and heterosis for seed yield per plant, while Maya × Basanti*hybrid was promising for oil content. The above results demonstrate that the parental genotypes and hybrids identified above can be used effectively in the improvement programs of Indian mustard. Hybridization coupled with pedigree breeding and recurrent selection will allow the development of improved varieties of mustard taking into account additive as well as non-additive genetic effects

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