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COMBINING ABILITY AND HETEROSIS FOR EARLY MATURITY AND YIELD-CONTRIBUTING TRAITS IN FIELD MUSTARD (*BRASSICA RAPA* L.)

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SUMMARY

Heterosis and combining ability are reputable fundamental breeding tools in assessing the performance of hybrids and the extent of the parents' combining ability. In the present study, evaluating 11 yield-attributing traits of 15 hybrids of the field mustard (*Brassica rapa* L.) helped estimate the magnitude and direction of combining ability and heterotic effects. The hybrids evolved from six diverse parents following a half-diallel mating scheme at the research farm of Sher-e-Bangla Agricultural University. The GCA effects showed that parents BARI-12, BARI-17, and BINA-10 for early maturity and plant height, while the parents BARI-6, BARI-14, and Maghi can be favorable as potential parents for yield-attributing traits. The hybrids BARI-6 × BARI-12 and BARI-12 × BINA-10 exhibited maximum negative SCA and heterotic effects for early maturity, and the hybrids BARI-12 × BARI-17 and BARI-14 × Maghi had the highest negative effects for plant height. Moreover, for yield and yield-contributing traits, hybrids BARI-6 × BARI-14, BARI-14 × Maghi, and BARI-17 × Maghi manifested higher SCA and heterotic effects than the other hybrids. The phylogeny and clustering analysis showed the developed hybrids have quite diversity, having been positioned in different clades. It suggests breeding superior recombinants could be effective from the segregating populations of hybrids.

Keywords: Mustard (*B. rapa* L.), combining ability, heterosis, genetic distance, early maturity, high-yielding hybrids

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Key findings: Promising findings indicate the early maturity and short-stature phenotypes incurred controlled by additive genetic effects. In general, non-additive gene action regulates the inheritance of most of the yield-attributing traits in *B. rapa* L. Overall, the hybrids, viz., BARI-6 × BARI-14, BARI-12 × BARI-17, and BARI-17 × Maghi could become potential lines in *B. rapa* L. breeding programs.

INTRODUCTION

The evolution of hybrid vigor through heterosis breeding is an incomparable phenomenon in crop improvement programs. The allelic and non-allelic interactions raise the heterozygosity in hybrids, making the hybrids more resistant to biotic and abiotic stresses with higher yield performance (Shull, 1908; Jones, 1917). Plant breeders used the heterosis breeding approach as a simple, quick, and effective method to maximize yield performance. However, heterosis exploitation has a high correlation with the parent's genetic divergence. The more diverse parents are highly considerable in heterosis breeding programs, as hybrids will highly succeed in obtaining from the parents having greater genetic distance to possibly manifest high heterotic effects (Zada *et al.,* 2013; Tian *et al.,* 2017). Therefore, the selection of the most suitable parents in heterosis breeding programs is a highly regarded and important step in mating design.

Identifying suitable parents is a prerequisite in hybridization, as it seems that favorable genes accumulate from parents to the offspring due to their genetic complementary effects; hence, hybrids manifest better performance (Mustafa *et al.,* 2023). Thus, the estimation of combining ability, including the general and specific combining ability effects, is a reliable tool in plant breeding to select suitable parents and cross-combinations, respectively. Besides, the nature and magnitude of gene actions help plant breeders to predict the prevailing gene actions, viz., additive and non-additive gene influences.

The gene actions that regulate the heredity of the quantitative traits can be beneficial in fabricating an efficient selection strategy (Jiangshuo *et al.,* 2017). Earlier, several researchers suggested that the knowledge of heterosis, together with combining ability effects, greatly enhances the efficiency of heterosis breeding programs in improving the hybrid's performance in *Brassica rapa* L. (Liton *et al*., 2017; Kechu and Barua, 2020). Considering the success of previous workers, in the current investigation, the combining ability and heterosis effects of 15 hybrids sustained assessment and, later, served as the basis for selecting the specific parents and hybrid combinations.

Worldwide, edible oil is a recognized beneficial source for the human diet for its higher nutritive and medicinal value. In fiscal year 2019–2020, oil production accounted for 203.91 metric tons globally, of which 26.67 metric tons from rape seeds (www.statistica.com). In Bangladesh, *Brassica rapa* L. is the most popular oilseed crop due to its shorter cultivation period and suitability in existing cropping patterns (Sultana *et al.,* 2021; Rahman *et al.,* 2022). Among the oil crops, rapeseed-mustard holds the first position, with a cultivated area of 270,023.26 ha, producing 311,740 metric tons of oilseed in 2018–2019 (BBS, 2019). In Bangladesh, the total consumption of oils and fats was 3.04 million tons (BER, 2019); however, the local production of edible oil meets only around 12% of the requirement (Mondal *et al*., 2023). The rest required importation by spending valuable foreign currency.

Therefore, an effort should be proceeded to develop short-duration and high-yielding varieties with higher seed oil percentages to meet the country's edible oil demand by boosting yield performance. In Bangladesh, the development of several varieties of *Brassica rapa* L. has progressed, but none of the varieties are early maturing and high-yielding. Therefore, the study focused on estimating the combining ability and heterosis effects to select superior breeding lines from earlier developed lines. The selected lines can be effective in breeding programs to develop high-yielding and short-maturing *B. rapa* L. cultivars.

MATERIALS AND METHODS

In this experiment, plant materials employed total of 21, including 15 F_1 hybrids and six parents. Developing early maturing and high-yielding cultivars of *B. rapa* L. had six popular varieties collected from the Bangladesh Agricultural Research Institute (BARI sharisha-6, BARI sharisha-12, BARI sharisha-14, and BARI sharisha-17) and a local variety called Maghi. The BINA sharisha-10 came from the Bangladesh Institute of Nuclear Agriculture. These varieties underwent cross-breeding following a half-diallel mating scheme, omitting the reciprocals in the rabi season of 2016–2017. The obtained 15 F_1 seeds' collection occurred separately. Then, sowing the seeds of 15 hybrids and their six parents together commenced during the 2017–2018 rabi season at the farm of Sher-e-Bangla Agricultural University, following RCBD (randomized complete block design), including three replications. The field allotment was 300 m^2, maintaining 0.75 m spacing between replications, 30 cm between rows, and 5 cm between plants. All fertilizer doses and intercultural practices followed the recommendations of the handbook of BARI, 2019. Picking 15 plants from each line transpired for recording the data for 11 yield-attributing traits. These are days to first flowering, days to 50% flowering, days to maturity, plant height (cm), primary branches plant^{-1}, secondary branches plant^{-1}, siliquae plant^{-1}, siliquae length (cm), seeds siliquae^{-1}, 1000-seed weight (g), and seed yield plant^{-1} (g).

Statistical analysis

The F-test (variance ratio) used helped analyze the variance, with the least significant difference ($LSD_{0.05}$) test performed to compare treatments. The variance analysis and F-test process used the Statistix-10 software, while the combining ability effects, gene actions of parents and hybrids, and cluster distance among the populations reached computations using the R-software (version R-4.3.3).

The heterosis effects estimation continued by comparing the mean values with the better parent (Heterobeltiosis) and the check variety (standard heterosis) by the following formulas:

$$\% \text{ Heterobeltiosis, (HB)} = \frac{F1-BetterParent}{BetterParent} \times 100$$

and

$$\% \text{ Standard heterosis, (HS)} = \frac{F1-CheckVariety}{CheckVariety} \times 100.$$

Using the standard error helped in determining the significance levels of heterosis.

RESULTS AND DISCUSSION

Mean performance

Development of hybrids with early maturity, short-stature phenotype, and higher seed yields is highly desirable in *Brassica rapa* L. improvement programs, as brown mustards are extensively cultivated crops in Asia due to shorter harvesting periods. In the current experiment, assessing hybrid performance ensued by evaluating 11 yield-related quantitative traits (Figures 1a and 1b). Among the hybrids, BARI-12 × BINA-10 (80.00 DAS), BARI-14 × BINA-10 (80.33 DAS), BARI-6 × BARI-12 (80.33 DAS), and BARI-6 × BINA-10 (80.67 DAS) required less duration for siliquae maturity than the early maturing parent BARI-14 (81.33 DAS). Furthermore, the shortest plant among the hybrids resulted in BARI-12 × BARI-17 (69.83 cm), followed by BARI-14 × BARI-17 (82.23 cm) and BARI-14 × Maghi (83.09 cm). They are almost similar in height to the short-stature parent BINA-10 (78.64 cm), indicating that complementary gene actions were predominant among these hybrids.

Regarding yield-contributing traits, the highest siliquae plant^{-1} within the hybrids was

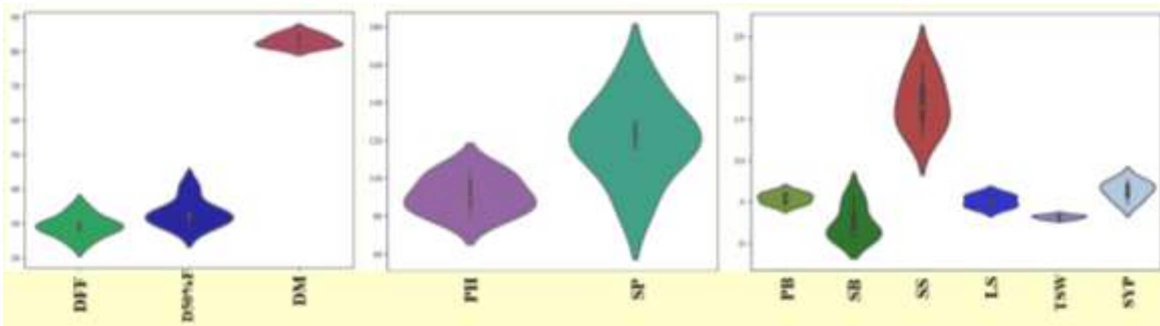

Figure 1a. Assessing the mean performance of six parents for 11 yield and yield-contributing traits of *B. rapa* L.

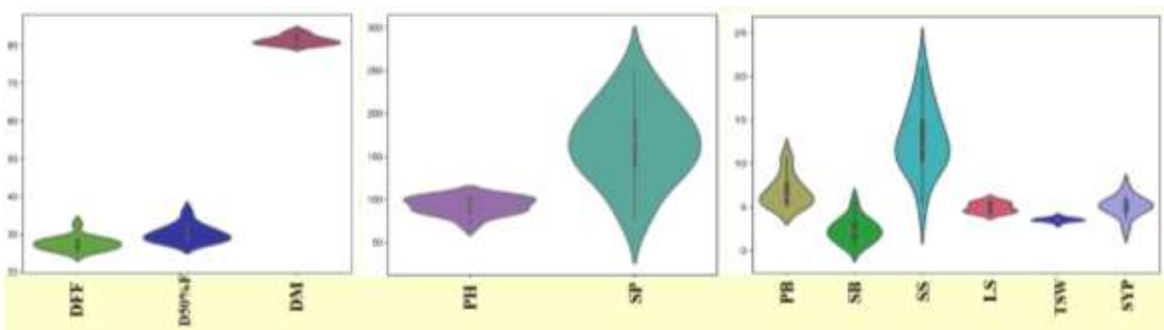

Figure 1b. Assessing the mean performance of 15 hybrids for 11 yield and yield-contributing traits of *B. rapa* L. Note: DFF= Days to 1st flowering, D50%F= Days to 50% flowering, DM= Days to maturity, PH= Plant height (cm), PB= Primary branches plant^{-1}, SB= Secondary branches plant^{-1}, SP= Siliquae plant^{-1}, LS= Siliquae length (cm), SS= Seeds siliquae^{-1}, TSW= 1000 seed weight (g), and SYP= Seed yield plant^{-1} (g).

prominent in BARI-6 × BARI-14 (247.93), BARI-17 × Maghi (224.33), and BARI-17 × BINA-10 (210.40), surpassing the superior siliquae-producing parent BARI-12 (151.80). Moreover, the maximum thousand seed weight in hybrids appeared in BARI 14 × Maghi (4.00 g), preceded by BARI-6 × BARI-14 (3.73 g) and BARI-14 × BINA-10 (3.73 g). They are much higher than the parent Maghi (3.47 g) that produced the utmost seed weight, indicating the accumulation of favorable genes responsible for siliquae number and seed weight from parents to the hybrids that manifest high vigor. However, the seed numbers per siliquae within the hybrids showed moderate performance compared with the parents. The seed yield plant^{-1} of hybrids viz., BARI-12 × BARI-14 (7.57 g), BARI-6 × BARI-14 (7.40 g), and BARI-6 × Maghi (7.23 g) exhibited statistically similar performance, which was better than the maximum seed yield-producing parent Maghi (7.22 g). Previously, Liton *et al.* (2017), Sultana *et al.* (2021), and Shelly *et al.* (2023) observed similar mean performances in *Brassica rapa*. They suggested hybrids showing early maturity and high-yielding phenotypes could be options as potential lines in the next breeding programs to obtain the desired recombinants.

Heterogeneity among the breeding populations

Hybridization is a well-recognized phenomenon in breeding that creates genetic variability by accumulating desirable alleles from diverse parents. The degree of prevailing genetic variability among the populations provides a meaningful indication for predicting expected heterosis or hybrid vigor. Cluster analysis measures genetic distances between genotypes and is a frequently used tool by scientists to identify and classify genotypes with similar attributes, as well as to separate one group of individuals from another (Tiwari and Misra, 2011). Considering these, the presented study computed the cluster analysis, and from the phylogenetic analysis, it was apparent that the hybrids and their respective parents were well diversified (Figure 2). Among the four clusters, cluster I included nine hybrids and three parents, cluster II included three hybrids, cluster III contained two parental lines and one hybrid, and cluster IV had two hybrids and one parent. The cluster distances obtained through the Euclidean complete method illustrate those hybrids under cluster I (5.13) and cluster II (5.02) had similar phenologies, as they possessed higher intra-cluster distances (Figure 3).

On the other hand, hybrids in cluster III (4.71) and cluster IV (3.68) were highly heterogeneous, as they showed the lowest intra-cluster distances. Therefore, one can expect that these hybrids, viz., BARI-6 × BARI-14, BARI-6 × BARI-17, and BARI-14 × Maghi, would manifest strong heterotic effects for yield-contributing traits. On inter-cluster distances, the maximum genetic variability was notable between cluster II and cluster III (7.84), followed by cluster I and cluster II (7.39), indicating that hybrids within these clusters possessed the highest variation. Their parents, Maghi, BARI-6, BARI-12, BARI-14, and BINA-10, involved in the combination of these hybrids, showed optimum genetic distances. Therefore, these hybrids should remain in high consideration for the next breeding programs, as a recurrent or pedigree breeding scheme may aid in selecting potential segregants from these hybrids. Similarly, Das *et al*. (2013) and Peric *et al*. (2021) also claimed the estimation of genetic distance helped in predicting the performance of heterogeneous populations. Thereby, the creation and expansion of genetic variation through hybridization enhances the possibilities of isolating superior recombinants in crop improvement programs.

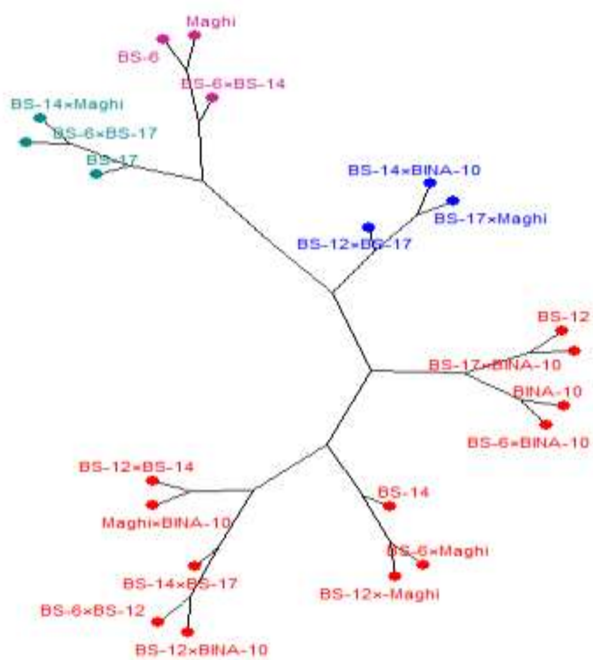

Figure 2. The phylogenetic tree of F_1 hybrids, including their parents, based on the mean performance of yield-contributing traits.

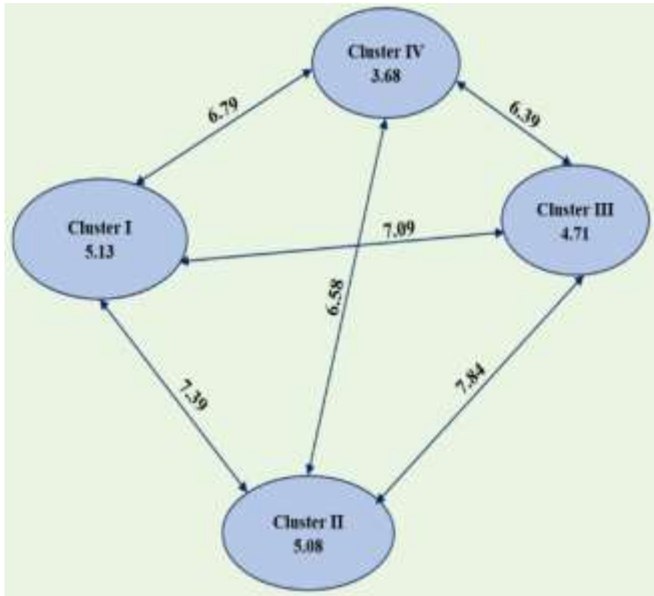

Figure 3. Average Intra- and Inter-cluster distances among the F_1 populations including their parents.

Combining ability effects

In crop improvement programs, the estimation of combining ability is a prerequisite in selecting suitable parents effective for use in developing improved hybrids adapted to a wide spectrum of agroecological zones. One can assume the notion obtained through the combining ability analysis provides breeders with an insight into the genetic makeup influencing the inheritance patterns of quantitative characteristics. Moreover, it can make a sound basis for predicting the hybrid's performance for future improvement in commercial hybrid breeding (Hayder and Paul, 2014). The obtained variance analysis of combining ability suggested significant genetic variability existed among GCA and SCA effects for all the traits (Table 1). Additionally, the larger effects of GCA than SCA indicated that inheritance patterns of days to first flowering, days to 50% flowering, days to maturity, plant height, secondary branches, siliquae length, seeds siliquae^{-1}, and thousand seed weight were notably under the additive gene action control. Hence, developing improved hybrids based on these traits is possible by accumulating favorable genes from parents to offspring. Huang *et al.* (2010) and Gul *et al.* (2018) claimed the dominant genetic effects were predominant among the traits of rapeseeds. Conversely, the heredity of three traits, viz., primary branches, siliquae plant^{-1}, and seed yield plant^{-1}, was largely with regulated non-additive gene action.

Mean performance with general combining ability makes the selection of parents more reliable in hybridization programs, as the previous finding provides authenticity to GCA effects as a direction for isolating suitable parents (Chaurasia *et al.,* 2020). A parent with substantial GCA effects in a desired direction is considered an excellent general combiner. One can expect that hybrids evolved from the good general combiners show stable and improved performance over the populations, as control of GCA effects came from the fixable nature of gene action (Singh *et al.,* 2022). In the presented experiment, none of the parents showed consistent GCA effects for all the selected traits (Table 2).

Regarding early maturity, parents, viz., BARI-14 (-0.49*), Maghi (-0.40*), and BINA-10 (-0.32) exhibited the desired negative GCA effects, whereas parents BINA-10 (-5.54**) and BARI-17 (-4.51**) could be a choice for superior general combiners in developing short-stature plants. Concerning yield-

Table 1. Analysis of variances for GCA and SCA for 11 characteristics of 6 parents and their 15 F_1s of *B. rapa* L.

Sources	d.f.	DFF	D50%F	DM	PH	PB	SB	SP	LS	SS	TSW	SYP
GCA	5	27.43**	42.99**	7.11**	504.75**	3.53*	15.29**	596.31**	1.37**	88.45**	0.32**	3.88*
SCA	15	11.29*	23.03**	6.71**	212.90**	9.69**	4.17**	7,750.39**	0.86**	38.88*	0.20**	5.11**
Error	40	5.69	4.88	1.47	27.88	1.14	0.63	64.12	0.21	3.09	0.03	1.35
GCA: SCA		2.43	1.87	1.06	2.37	0.36	3.67	0.08	1.61	2.28	1.60	0.76

Note: DFF= Days to 1st flowering, D50%F= Days to 50% flowering, DM= Days to maturity, PH= Plant height (cm), PB= Primary branches plant^{-1}, SB= Secondary branches plant^{-1}, SP= Siliquae plant^{-1}, LS= Siliquae length (cm), SS= Seeds siliquae^{-1}, TSW= 1000 seed weight (g), SYP= Seed yield plant^{-1} (g). *= *P* > 0.05, **= *P* > 0.01, ns= nonsignificant.

Table 2. Estimation of general combining ability (GCA) for 11 characteristics of 6 parents of *B. rapa* L.

Parents	DFF	D50%F	DM	PH	PB	SB	SP	LS	SS	TSW	SYP
BARI 6	0.64	0.64	0.81**	6.95**	-0.52	-0.40	-4.47**	0.38	1.75	-0.01	0.45*
BARI 12	-0.69	-0.86*	-0.15	2.10	-0.42	0.90	1.24	-0.02	-2.59*	-0.10	-0.30
BARI 14	-0.32	-0.19	-0.49*	-0.21	0.26	-0.63	3.07*	-0.15	0.64	0.15	0.42*
BARI 17	1.56*	2.01**	0.56	-4.51**	0.14	-0.46	-3.74 **	-0.30	-0.33	0.03	-0.29
Maghi	0.31	0.31	-0.40*	1.21	0.42	-0.55	-4.04**	0.16	2.26*	0.08	0.34*
BINA 10	-1.49*	-1.90**	-0.32	-5.54**	0.13	1.15*	7.94 **	-0.07	-1.73	-0.16*	-0.49**
SE gij	0.45	0.41	0.23	0.98	0.20	0.15	1.49	0.09	0.33	0.03	0.22
SE (gi-gj)	0.69	0.64	0.35	1.52	0.31	0.23	2.31	0.13	0.51	0.05	0.34

Note: DFF= Days to 1st flowering, D50%F= Days to 50% flowering, DM= Days to maturity, PH= Plant height (cm), PB= Primary branches plant^{-1}, SB= Secondary branches plant^{-1}, SP= Siliquae plant^{-1}, LS= Siliquae length (cm), SS= Seeds siliquae^{-1}, TSW= 1000 seed weight (g), SYP= Seed yield plant^{-1} (g). *= *P* > 0.05, **= *P* > 0.01, ns= nonsignificant.

contributing traits, parents BARI-6 (0.45*), BARI-14 (0.42*), and Maghi (0.34*) could possibly be effective, and excellent breeding materials in generating high-yielding hybrids. The current findings are comparable to Nasim *et al.* (2014), Snehi *et al.* (2019), and Liton *et al.* (2020). Therefore, the estimated magnitude of the GCA effects of these parents provides the breeders with meaningful information for future breeding programs.

Estimation of the specific combining ability (SCA) of hybrids is a highly important feature in selecting the superior hybrids by producing better or worse outcomes than expected compared with their parents' average performance. Since the effects of SCA are under the non-additive gene action control, viz., dominance, additive × dominance, epistasis, and the hybrids with the desired SCA effects were more heterogeneous. Therefore, it is valid that these hybrids manifested better heterotic effects (Kaur *et al.,* 2020). In the relevant study, SCA effects varied significantly for all the traits (Table 3). Among the 15 hybrids, 10 hybrids showed the expected negative SCA effects, wherein BARI-6 × BARI-12 (-2.21*), BARI-6 × BINA-10 (-1.71), and BARI-17 × Maghi (-1.38) exhibited the topmost SCA effects for maturity duration. Meanwhile, only four hybrids had the negative SCA effects, in which BARI-12 × BARI-17 (-20.01**), BARI-14 × Maghi (-10.16**), and BARI-6 × BINA-10 (-8.22**) showed the top performance for plant height. Hence, the above-mentioned hybrids could be options for developing the early maturing and short-stature cultivars of *B. rapa* L.

Table 3. Estimation of specific combining ability (SCA) for 11 characteristics of 15 F_1s of *B. rapa* L.

F_1 Hybrids	DFF	D50%F	DM	PH	PB	SB	SP	LS	SS	TSW	SYP
BARI 6 × BARI 12	-1.98 *	-2.71**	-2.21*	0.27	-0.07	-0.07	-5.79 **	-0.17	-0.98	0.21	-1.00
BARI 6 × BARI 14	-0.02	0.29	0.46	4.54**	0.85	0.66	96.92 **	0.40	0.59	0.16	1.22*
BARI 6 × BARI 17	2.44*	2.41*	0.42	3.23**	-0.43	-1.18	-43.82 **	-0.46	-0.91	0.21	-0.14
BARI 6 × Maghi	-0.64	-0.21	-1.29	2.70**	1.02	1.18	26.22 **	-0.18	-0.07	-0.04	-1.04
BARI 6 × BINA 10	-1.19	-1.34	-1.71	-8.22**	0.11	0.55	-19.23 **	0.29	1.16	-0.26	-0.55
BARI 12 × BARI 14	-1.35	0.12	-0.92	4.05**	-0.59	-0.37	-15.99 **	-0.49	-2.46*	-0.09	1.13
BARI 12 ×BARI 17	-1.23	-1.76	-0.63	-20.01**	-0.66	-1.01	-17.79 **	-0.44	-5.77**	0.26	-2.53 **
BARI 12 × Maghi	1.02	0.62	-0.33	8.45**	1.65	-0.79	24.12 **	-0.45	-3.56**	0.08	0.78
BARI 12 × BINA 10	0.82	0.16	-1.42	0.18	-1.06	-0.91	21.67 **	0.64	0.77	0.23	0.67
BARI 14 × BARI 17	-2.94**	-4.42**	-0.63	-5.29**	-1.48	0.99	44.52 **	1.23	0.14	0.11	1.04
BARI 14 × Maghi	0.98	2.29*	1.00	-10.16**	-1.30	-0.33	-72.44 **	0.05	4.11**	0.33	-1.61*
BARI 14 × BINA 10	0.12	-0.51	-0.75	0.19	3.93**	-1.88	22.77 **	-0.25	-2.46*	0.31	-0.05
BARI 17 × Maghi	-3.89**	-5.59**	-1.38	13.29**	3.29**	-0.37	79.69 **	-0.44	-4.23**	-0.05	1.13
BARI 17 ×BINA 10	-0.10	-1.38	1.54	4.09 **	1.32	2.48*	53.77 **	-0.20	-1.37	0.13	0.44
Maghi × BINA 10	1.15	-0.01	0.83	3.04 **	-0.64	0.63	-3.52 **	-0.20	-2.69**	-0.05	-1.70*
SE (sij)	1.22	1.13	0.62	2.70	0.55	0.41	4.10	0.23	0.90	0.09	0.60
SE (sij-skl)	1.69	1.56	0.86	3.73	0.76	0.56	5.66	0.32	1.24	0.13	0.82

Note: DFF= Days to 1st flowering, D50%F= Days to 50% flowering, DM= Days to maturity, PH= Plant height (cm), PB= Primary branches $plant^{-1}$, SB= Secondary branches $plant^{-1}$, SP= Siliquae $plant^{-1}$, LS= Siliquae length (cm), SS= Seeds $siliquae^{-1}$, TSW= 1000 seed weight (g), SYP= Seed yield $plant^{-1}$ (g). *= *P* > 0.05, **= *P* > 0.01, ns= nonsignificant.

Considering the yield and yield-attributing traits of hybrids, eight and five hybrids had the desired positive SCA effects for the siliquae $plant^{-1}$ and seeds $siliqua^{-1}$, respectively. Similarly, 10 and five hybrids showed positive SCA effects for thousand seed weight and seed yield, respectively. Altogether, four hybrids, including BARI-6 × BARI-14 (1.22*), BARI-12 × BARI-14 (1.13), BARI-17 × Maghi (1.13), and BARI-14 × BARI-17 (1.04) could become selections for promising specific combiners for developing high-yielding hybrids. However, a superior specific combiner can produce cross-combinations of parents that contain low to high GCA effects. Several workers, viz., Gupta *et al.* (2010), Azizinia *et al.* (2012), and Meena *et al.* (2017) also reported similar findings. Among the selected hybrids for seed yield, hybrid BARI-6 × BARI-14 emerged with the combinations of good general combiners, indicating the dominance of additive genetic effects. Meanwhile, BARI-12 × BARI-14, BARI-17 × Maghi, and BARI-14 × BARI-17 evolved from the interaction of low × good and low × low general combiners, suggesting that additive × epistatic or dominant gene actions may control the heredity. Mamun *et al.* (2022) reported the complementary gene action plays a pivotal role in generating higher SCA effects in hybrids obtained from parents with low to average GCA effects.

Heterotic effects

Heterosis is commonly applicable in developing vigor hybrids, as it denotes the heterozygote nature of crosses that evolved from two or more diverse parents through hybridization. Hybrids manifest better heterotic effects than the parents and may also exhibit higher yield, disease resistance, and tolerance to biotic and abiotic stresses. Thereby, it enhances the economic outcome of the developed cultivars (Zhang *et al.,* 2021). For the estimation of

Table 4. Estimation of heterosis over better parent (BP) and check varieties, CV (BARI Sarisha-14) in 15 F_1 hybrids of *B. rapa* L.

F_1 Hybrids	Heterosis	DFF	D50%F	DM	PH	PB	SB	SP	SL	SS	TSW	SYP
BARI 6 × BARI 12	BP	5.39 **	-2.34	-1.23	-3.15	-12.90**	-50.88**	-5.53	-11.86 **	-43.96 **	0.00	-3.62 **
	CV	-10.35**	-11.59**	-1.23	10.09 **	-12.90**	75.00 **	18.84	23.81 **	-20.42 **	6.06**	-2.64**
BARI 6 × BARI 14	BP	14.84**	10.46**	1.65	-1.29	12.90**	-64.91**	63.33*	-5.09 **	-21.91 **	5.71**	8.35 **
	CV	-2.31	0.00	1.65	12.21**	12.90**	25.00 **	105.46 **	33.33 **	10.89 **	12.12**	10.23 **
BARI 6 × BARI 17	BP	32.43**	25.57**	2.88**	-6.64	-9.68**	-94.74**	-33.86	-22.03 **	-33.26 **	5.71**	-14.49 **
	CV	12.66**	13.67**	2.88**	6.12	-9.68**	-81.25 **	-16.80	9.52 **	-5.22	12.12**	-12.88**
BARI 6 × Maghi	BP	14.84**	10.46**	0.41	-1.67	17.74**	-54.39**	12.08	-10.17 **	-17.46 **	0.00	0.14 **
	CV	-2.31	0.00	0.41	11.77**	17.74**	62.50 **	40.99	26.19 **	17.22 **	6.06**	8.46**
BARI 6 × BINA 10	BP	5.39 **	-1.19	-0.81	-18.54**	-1.61*	-35.09**	-9.97	-5.09 **	-30.18 **	-14.29**	-29.42**
	CV	-10.35**	-10.55**	-0.81	-7.40	-1.61*	131.25 **	13.26	33.33 **	-0.85	-9.09**	-29.47**
BARI 12 × BARI 14	BP	4.05*	4.64**	-1.23	-6.38	-8.07**	-59.65**	-7.29	-27.12 **	-55.90 **	-2.86**	10.83**
	CV	-11.48**	-5.27**	-1.23	6.42	-8.07**	43.75 **	16.62	2.38 **	-37.38 **	3.03**	10.00**
BARI 12 ×BARI 17	BP	12.16**	5.79**	0.42	-33.41**	-11.29**	-68.42**	-12.96	-28.81 **	-75.52 **	2.86**	-29.02**
	CV	-4.59**	-4.23**	0.42	-24.31**	-11.29**	12.50 **	9.50	0.00	-65.23 **	9.09**	-42.37**
BARI 12 × Maghi	BP	16.21**	8.13**	0.41	-0.82	30.65**	-66.67**	14.45	-20.34 **	-53.47 **	0.00	-13.16**
	CV	-3.45*	2.12	0.41	12.74**	30.65**	18.75 **	43.97	11.91 **	-33.92 **	6.06**	-7.75 **
BARI 12 × BINA 10	BP	8.11 **	0.00	-1.64*	-15.13**	-17.74**	-38.60**	20.73	-6.78 **	-51.91 **	-2.86**	-12.62 **
	CV	-8.03**	-9.47**	-1.64*	-3.53	-17.74**	118.75 **	51.88	30.95 **	-31.70 **	3.03**	-30.80**
BARI 14 × BARI 17	BP	6.73 **	-1.19	0.00	-21.59**	-14.52**	-59.65**	29.30	-1.70 **	-33.53 **	5.71**	4.39 **
	CV	-9.21**	-10.55**	0.00	-10.87**	-14.52**	43.75 **	62.65*	38.10 **	-5.61	12.12**	3.96**
BARI 14 × Maghi	BP	17.55**	16.25**	0.82	-20.77**	-6.45**	-84.21**	-47.96	-13.56 **	-3.40	14.29**	-38.09 **
	CV	0.00	5.24**	0.82	-9.94*	-6.45**	-43.75 **	-34.53	21.43 **	37.18 **	21.21**	-54.50**
BARI 14 × BINA 10	BP	6.73 **	-1.19	-1.23	-11.82**	72.58**	-82.46**	22.66	-23.73 **	-51.91 **	5.71**	-23.87 **
	CV	-9.21**	-10.55**	-1.23	0.23	72.58**	-37.50 **	54.31	7.14 **	-31.70 **	12.12**	-26.00**
BARI 17 × Maghi	BP	1.34	-3.49*	-0.81	-2.52	66.13**	-82.46**	47.78	-25.42 **	-46.12 **	0.00	-4.02 **
	CV	-13.79**	-12.63**	-0.81	10.81**	66.13**	-37.50 **	85.90**	4.73 **	-23.48 **	6.06**	1.88**
BARI 17 ×BINA 10	BP	13.50**	3.49*	2.88 **	-17.72**	29.03**	-3.51**	38.60	-25.42 **	-51.31 **	-2.86**	4.13 **
	CV	-3.45*	-6.32**	2.88**	-6.47	29.03**	43.75 **	74.36*	4.76 **	-30.86 **	3.03**	-14.45**
Maghi × BINA 10	BP	13.50**	2.30	0.82	-13.26**	1.61*	-36.84**	0.66	-16.95 **	-45.48 **	-5.71**	-45.84 **
	CV	-3.45*	-7.39**	0.82	-1.40	1.61*	125.00 **	26.63	16.67 **	-22.57 **	0.00	-65.32**

Note: DFF= Days to 1st flowering, D50%F= Days to 50% flowering, DM= Days to maturity, PH= Plant height (cm), PB= Primary branches plant^{-1}, SB= Secondary branches plant^{-1}, SP= Siliquae plant^{-1}, LS= Siliquae length (cm), SS= Seeds siliquae^{-1}, TSW= 1000 seed weight (g), SYP= Seed yield plant^{-1} (g). *= P > 0.05, **= P > 0.01, ns= nonsignificant.

standard or economic heterosis, using a commercially grown popular variety often helps to compare the performance of the hybrid. In this experiment, a popular mega-variety of *B. rapa,* the BARI sharisha-14 (CV), served as a check variety for comparing 11 yield-related traits of the 15 hybrids. Additionally, determining the effects of heterosis over better parents also proceeded. However, the estimated heterosis differed from trait to trait for each cross (Table 4).

For early maturity and short-stature plants, expecting negative effects of heterosis is valid. Among the 15 hybrids, five and six hybrids manifested negative heterotic effects over the better parent and check varieties for days to 50% flowering and days to maturity, respectively. The hybrids BARI-12 × BINA-10 (-1.64* and -1.64*), BARI-6 × BARI-12 (-1.23 and -1.23), BARI-12 × BARI-14 (-1.23 and -1.23), and BARI-14 × BINA-10 (-1.23 and -1.23) manifested the top-ranked heterotic effects over better parent and check variety, respectively, for early maturity. They could be useful for obtaining the desired recombinants in future generations.

In getting the short-stature plants, hybrids including BARI-12 × BARI-17 (-33.41** and -24.31**), BARI-14 × BARI-17 (-21.59** and -10.87**), and BARI-14 × Maghi (-20.77** and -9.94*) could be beneficial in future breeding due to their topmost negative heterotic effects over both indexes, respectively. Both for early maturity and short plant height, the selected hybrids shared the maximum general and specific combiners, suggesting that dominant gene action governs the trait's behavior. Similar negative heterotic effects resulted for early maturity and plant height in *B. rapa* (Nasim *et al.,* 2014; Liton *et al.*, 2017). Regarding yield-related traits, positive heterotic effects are desirable. Eight hybrids manifested positive heterosis over the better parent and check varieties. Among them, BARI-6 × BARI-14 (63.33* and 105.46**), BARI-17 × Maghi (47.78 and 85.90**), and BARI-17 × BINA-10 (38.60 and 74.36*) had the premier heterotic effects for the siliquae plant^{-1}. Meanwhile, 10 hybrids revealed the desired heterotic effects for thousand seed weight over both levels, in which BARI-14 × Maghi (14.29** and 21.21**), BARI-14 × BARI-17 (5.71** and 12.12**), and BARI-6 × BARI-14 (5.71** and 12.12**) provided the highest positive effects. This indicated that genes responsible for siliquae number and seed weight reached accumulation from the diverse parents, and due to the optimum heterozygosity, hybrids exhibited high vigor for these traits (Zada *et al.,* 2013; Tian *et al.,* 2017).

For the seeds siliquae^{-1}, none of the hybrids displayed positive heterosis over the better parent, while only three hybrids, viz., BARI-14 × Maghi (37.18**), BARI-6 × Maghi (17.22**), and BARI-6 × BARI-14 (10.89**) had the desired heterotic effects over the check variety. Furthermore, out of 15 hybrids, five hybrids showed positive standard heterosis for seed yield plant^{-1} over the check variety, whereas the heterobeltiosis for seed yield was positive for five hybrids. Altogether, hybrids BARI-6 × BARI-14 (8.35** and 10.23**), BARI-12 × BARI-14 (10.83** and 10.00**), and BARI-14 × BARI-17 (4.39* and 3.96*) could be choices as they manifested the top-ranked heterotic effects over better parent and check variety, respectively, for seed yield. These results are greatly analogous to the findings of Chaudhari *et al.* (2015), Kechu and Barua (2020), and Mahanta and Barua (2020). Furthermore, the hybrid BARI-6 × BARI-14 had the highest heterotic effects for seed yield. This could be because it contained good general combiners and also showed the desired specific combining effects, indicating the additive gene action was predominant. Inversely, the other hybrids had low to average general combiner with lower and non-significant SCA effects. Therefore, the GCA effects of parents and SCA effects of hybrids acted as good indicators in predicting the hybrid's heterosis performance. However, these potential hybrids required further assessments at farmer’s fields to determine the performance of stability in diverse climatic conditions.

CONCLUSIONS

Authors found both additive and non-additive genetic effects played pivotal roles in controlling the inheritance of the traits in *B. rapa* L. Collectively, hybrids BARI-6 × BARI-14, BARI-14 × Maghi, and BARI-17 × Maghi manifested the desired heterosis and specific combining effects for yield-attributing traits. The hybrids, BARI-12 × BARI-17, BARI-12 × BINA-10, and BARI-14 × BINA-10 were the most recommended samples for developing early-maturing and short-stature breeding lines from their segregating populations.

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REFERENCES

Azizinia S (2012). Combining ability analysis of yield component parameters in winter rapeseed genotypes (*Brassica napus* L.). *J. Agric. Sci*. 4(4): 87–94.

BBS (2019). Statistical Yearbook of Bangladesh. Bangladesh Bureau of Statistics, Statistics Division, Ministry Planning, Govt. People's Republic of Bangladesh, Dhaka. pp. 125.

BER (2019). Bangladesh Economic Review (BER), Economic Division, Ministry of Finance, Dhaka. pp. 83.

Chaudhari NH, Patel RN, Gami RA, Shah SK (2015). Study of combining ability and heterosis for seed yield. *Bioscan* 10(4): 1985–1989.

Chaurasia NK, Nirala RBP, Singh B (2020). Combining ability and heterosis studies in maize (*Zea mays* L.) under Kharif season. *Int. J. Curr. Microbiol. Appl. Sci.* 9(11): 2576–2586.

Das A, Pandey S, Dasgupta T (2013). Association of heterosis with combining ability and genetic divergence in sesame (*Sesamum indicum* L.). *Int. J. Sci. Technol. Res.* 2(12): 307–314.

FAO (2019). Food and Agriculture Organization of the United Nations, FAOSTAT. FAO Statistic Division.

Gul SR, Uddin NU Khan, Arif MR, Gohar, Zakaria M (2018). Inheritance studies through combining ability for morphological and yield traits in F_1 populations of *Brassica napus* L. *J. Anim. Plant Sci.* 28(4): 1094–1102.

Gupta P, Chaudhary HB, Lal SK (2010). Heterosis and combining ability analysis for yield and its components in Indian mustard (*Brassica juncea* L. Czern & Coss). *Front. Agric. China* 4(3): 299–307.

Hayder FMA, Paul NK (2014). Combining ability analysis for different yield components in maize (*Zea mays* L.) inbred lines. *Bangladesh J. Plant Breed. Genet*. 27(1): 17–23.

Huang Z, Laosuwan P, Machikowa T, Chen Z (2010). Combining ability for seed yield and other characters in rapeseed. *Suranaree J. Sci. Technol*. 17(1): 39–47.

Jiangshuo S, Zhang F, Yang X, Feng Y, Yang X, *et al.* (2017). Combining ability, heterosis, genetic distance and their intercorrelations for waterlogging tolerance traits in chrysanthemum. *Euphytica* 213:42.

Jones DF (1917). Dominance of linked factors as a means of accounting for heterosis. *Genetics* 2(5): 466–479.

Kaur G, Kaur M, Kumar R (2020). Line × Tester analysis for quantitative traits in Indian mustard (*Brassica juncea* L.). *J. Oilseed Brassica* 11(1): 77–87.

Kechu S, Barua PK (2020). Genetic variability and character association in rapeseed (*Brassica rapa* L.) under organic cultivation. *Int. J. Cur. Microbiol. Appl. Sci.* 9(9): 3232–3239.

Liton MMUA, Bhuiyan MSR, Zeba N, Rashid MH (2017). Estimation of heterosis for yield and its attributes in *Brassica rapa* L. *Asian Res. J. Agri*. 4(4): 1–13.

Liton MMUA, Bhuiyan MSR, Zeba N, Rashid MH, Ali MA (2020). Combining ability and gene action analysis in the half-diallel cross of *Brassica rapa* L. *J. Agric. Sci. Prac*. 5(1): 20–29.

Mahanta M, Barua PK (2020). Combining ability, heterosis and maternal effects for yield and attributing traits in yellow sarson (*Brassica rapa* L. var. yellow sarson). *J. Pharmacog. Phytochem*. 9(4): 641–646.

Mamun M, Rafii MY, Misran AB, Berahim Z, Ahmad Z, Khan MMH, Oladosu Y (2023). Heterosis and combining ability estimate on yield and yield-related traits in a half diallel crosses of kenaf (*Hibiscus cannabinus* L.) in Malaysia. *J. Nat. Fibers*. 20(1).

Meena HS, Kumar S, Kulshrestha S, Meena PD, Ram B, Sharma A, Singh VV, Singh D (2017). Line × tester analysis for combining ability and heterosis in Indian mustard (*Brassica juncea*). *J. Oilseed Brassica* 1(1): 18–26.

Mondal S, Johora FT, Roy G, Rahman J (2023). Genotype and environment interactions of yield contributing characters of field mustard (*Brassica rapa*). *Bangladesh J. Bot*. 52(4), 1055–1065.

Mustafa SE, Razzaq H, Khan FA, Khan SH (2023). Estimation of combining ability effects for yield and fatty acid related traits in *Brassica rapa* using line by tester analysis. *SABRAO J. Breed. Genet.* 55(4): 1123–1131.

Nasim A, Farhatullah, Khan NU, Afzal M, Azam SM, Nasim Z, Amin NU (2014). Combining ability and heterosis for yield and yield contributing traits in *Brassica rapa* (L.) ssp. Dichotoma (Roxb) Hanelt. *Pak. J. Bot*. 46(6): 2135–2142.

Peric S, Stevanovic M, Prodanovic S, Drinic SM, Grcic N, Kandic V, Pavlov J (2021). Genetic distance of maize inbreds for prediction of heterosis and combining ability. *Genetika* 53(3): 1219–1228.

Rahman J, Sultana F, Fatima K, Hasan MM, Gain N, Hossain MS, Chowdhury AK, Rahman A (2022). Genetic diversity of field mustard (*Brassica rapa* L.) and their saturated and unsaturated fatty acids association. *SABRAO J. Breed. Genet*. 54(2): 249–266.

Shelly NJ, Bhuiyan MSR, Mahmud F, Rahman J, Alam MA (2023). Variability and heritability study in some selected *Brassica rapa* L. genotypes. *Bangladesh J. Agric.* 48(2): 106–118.

Shull GH (1908). The composition of a field of maize. *Am. Breeders Assoc. Rep.* 4: 296–301.

Singh VV, Balbeer HK, Priyamedha R, Meena HS, Rai PK (2022). Heterosis and gene action studies for agro-physiological traits in Indian mustard (*Brassica juncea* L.). *J. Pharma. Innov*. 11(5): 393–398.

Snehi S, Bhajan R, Pant U, Singh NK (2019). Combining ability and heterosis analysis for yield and contributing traits in local germplasm of yellow sarson (*Brassica rapa* var. Yellow Sarson Prain). *Int. J. Cur. Microbiol. Appl. Sci.* 8(07): 1120–1133.

Sultana F, Rahman J, Hasan MM (2021). Genetic variability and character association of Bangladeshi popular varieties of mustard (*Brassica rapa* L.). *J. Bangladesh Acad. Sci*. 44(2): 95–107.

Tian HY, Channa SA, Hu SW (2017). Relationships between genetic distance, combining ability and heterosis in rapeseed (*Brassica napus* L.). *Euphytica* 213(1): 1–11.

Tiwari M, Misra B (2011). Application of cluster analysis in agriculture. *Int. J. Comp. Appl.* 36(4): 43–47.

Zada M, Shinwari ZK, Zakir N, Rabbani MA (2013). Study of total seed storage proteins in Ethiopian mustard (*Brassica carinata* A. braun) germplasm. *Pak. J. Bot*. 45(2): 443–448.

Zhang S, Huang X, Han B (2021). Understanding the genetic basis of rice heterosis: Advances and prospects. *Crop J.* 9: 688–692.