Combining Ability and Potential Heterosis in Ethiopian Mustard (*Brassica carinata* A. Braun)

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Abstract: This study was conducted to estimate general and specific combining ability variances and potential heterosis in *Brassica carinata* A. Braun. Seven parental lines along with their 21 F_1 crosses were planted in 2009/2010 and 2010/2011 at the G.B. Pant University Crop Research Centre, India using randomized block design with three replications in three rows for each accession per replication. Data recorded for 14 traits were subjected to the Griffing (1956) method II model I genetic analysis and estimate of heterosis. Standard heterosis of the crop parameters ranged from -8.22% for harvest index to 191.57% for number of pods per plant, while for seed yield per plant it ranged from -16.64 to 66.09%. Both additive and non additive gene actions were important in controlling days to 50% flowering, pod length, percent oil content, plant height, length of main shoot, seed yield per plant, biological yield, harvest index, and number of primary and secondary branches. Additive gene action was important for the expression of days to 90% maturity, seeds per pod and thousand seeds weight. Non-additive gene actions were important in controlling the expression of pods per plant.

Keywords: *Brassica carinata*; Additive and Non-additive Gene Actions; Combining Ability; Standard Heterosis

1. Introduction

Ethiopian mustard is one of the oldest oil crops cultivated in Ethiopia (Simmonds, 1979) but is practically not much cultivated in any other part of the world. Because of its drought and heat tolerance, the crop is now considered as an alternative to *Brassica napus* and *Brassica juncea* in dryer areas of Canada, Spain, Australia, India, USA, and Italy (Velasco *et al*., 1995, Fletche, 1997, Cardone *et al*., 2003, Singh, 2003).

Brassica carinata is higher yielding, more resistant to diseases and insect pests, and resistant to seed shattering than *Brassica napus* with the additional agronomic advantages of better tolerance for semi-arid conditions (Malik, 1990). Hence, *Brassica carinata* can serve as an important source of genes, which are rare in other oilseed *Brassicas*. In different countries, different effort have been made to reduce its high erucic acid content and improve its oil quality to use as vegetable oil (Velasco *et al.,* 1995; Meng *et al.,* 1998; Singh, 2003).

One of the main challenges faced by mankind in the 21st century is to meet the increasing demand for energy requirements by means of a more sustainable energy supply. A strong interest is felt at the global level for diversification of energy sources, in order to be able to better prepare for eventual future oil crisis. *Brassica carinata*, has become the interest of European countries, Canada and Australia for biodiesel production (Smith *et al*., 1997; Bozzini *et al.,* 2007).

Ethiopian or Abyssinian mustard (*Brassica carinata)* is an important oil crop in Ethiopia and it is the third most important oil crop next to niger seed (*Guizotia abyssinica* Cass.) and linseed (*Linum usitatissimum* L) (CSA, 2003) in the highlands of this country. Traditional utilization of this crop embraces quite an array of purposes including as leafy vegetable. It is also eaten as a condiment or salad (Nigussie *et al.,* 1999).

Determination of the genetical structure of a crop and combining ability is necessary for improvement of the crop since it usually results in accurate and logical selection in hybridization programme for the possibility of producing the best hybrids. The quality and quantity of the genetic parameters like heterosis, gene action, general and specific combining ability of parents and their off-springs is possible via diallel analysis. In Ethiopian mustard studies that reveal gene action underlying a quantitative trait is scanty and as our knowledge permit only one experimental result was published on heterosis and combining ability of Ethiopian mustard (Adefris and Becker, 2005).

Line breeding and mass selection are the dominant breeding methods used to improve Ethiopian mustard. However, development of hybrid cultivars has been successful in other oilseed *Brassica* species. Studies in *Brassica napus, Brassica rapa* and *Brassica juncea* have indicated high levels of heterosis ranged from 29 to 200% heterosis over the best-yielding parents (Banga and Labana,1984; Pradhan *et al.,* 1993; Melchinger and Gumber, 1998; Becker *et al.,* 1999; Miller, 1999). Ethiopian mustard (BBCC) sharing one of its genome with *Brassica juncea* (AABB) and the other with *Brassica napus* (AACC) (U., 1935) could be amenable for heterosis breeding as to its close relatives. But, information regarding heterosis in *Brassica carinata* is scanty. Therefore, generating information regarding gene actions controlling yield and yield attributed traits and potential heterosis in Ethiopian mustard is important. The objectives of this study were i) to estimate the relative importance of general and specific combining ability variances and ii) to asses the potential of heterosis in Ethiopian mustard.

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2. Materials and Methods

Seven parental inbred lines namely; HCO-211, HCO-288, PBC-2005-1, Kiran (Bold), Kiran (Early), Jayanti and PBC-2006-4 were used in this study. These parental lines were selected for their yield potential and other desirable traits. Among the parental lines Kiran (Bold) was the commercial variety which was used as check as well as parental line in the experiment. Crossing between the parental inbred lines was made at the G.B. Pant Agriculture and Technology University Crop Research Center in the 2008/2009 and 2009/2010 cropping seasons. Crossing was done by hand emasculation and bud pollination on 25 to 35 plants per line in half-diallel fashion. Seeds of seven parental lines and 21 F_{1s}, were sown and grown for two cropping seasons (2009/2010 and 2010/2011). The experiments in both cropping seasons were laid out in randomized complete block design with three replications. Plots consisted three rows of 5 m length and 30 cm inter-row and 10 cm intra-row spacing. Crop management factors were applied as recommended for *Brassica* spp.

In both seasons, except days to 50% flowering and 90% plants maturity that were recorded on plot basis, the other phenotypic traits were recorded from the same 10 randomly selected plants of the central row as follows: days to flowering (days from sowing until about 50% of the plants flower); days to maturity (days from sowing until about 90% of the pods mature); number of primary branches per plant (productive branches originating from the main stem); number of secondary branches per plant (productive branches developed from the primary branches); number of pods per plant (pods borne on both primary and secondary branches); pod length (length of six individual pods per plant, two each from bottom-, middle-, and top-borne branches); plant height (main stem length); length of main shoot (from base of most top primary branch to the tip of the plant): number of seeds per pod (obtained from the same pods used to estimate pod length); seed yield per plant; 1000-seed weight (g); percentage oil content (determined by nuclear magnetic resonance spectrometry at Center for National Oil Seed, India); biological yield (selected plants harvested from the base, dried and weighted), harvesting index (seed yield per plant/biological yield per plant x 100).

Standard heterosis and critical differences to test the magnitude of SH were computed by considering the two years mean performance of parents and hybrids as follows: SH (%) = F_1- CV/CV x 100, CV stands for mean of commercial variety (Kiran bold), F_1 for mean of hybrids. Standard heterosis were tested as per the method proposed by Panse and Sukhatme (1961) which critical difference calculated as CD = $\sqrt{2xEMS/r}$ x t value at error degree of freedom.

Combining ability analysis was performed according to Griffing's method II- Model I (Griffing 1956), genetic component and accordingly variance ratio was calculated respect to this model. Data analysis was conducted using MSTAT-C 1986 Michigan University statistical soft ware. The data from the F_1 crosses and parents were subjected to analysis of variance for randomized complete block design. Further genetic analysis was performed for those parameters in which statistically significant differences existed among genotypes.

3. Results

Data recorded for 14 yield and yield attributing traits of *Brassica carinata* A. Braun genotypes were subjected to analysis of variance to assess the existence of differences among genotypes. Results obtained from combined analysis of two years data are present in Table 1. The combined analysis of variance included seven parental lines and 21 F_1 hybrids. The analysis results showed highly significant ($P < 0.01$) differences among genotypes for 13 out of 14 traits, while significant differences ($P < 0.05$) were detected for thousand seed weight. This allowed conducting further genetic analysis for all the studied traits.

3.1. Analysis of Combining Ability

3.1.1. Mean Squares

The pooled analysis of variance over two years for combining ability for different yield and yield attributing traits is presented in Table 2. The result showed that both GCA and SCA mean squares were highly significant for days to 50% flowering, number of primary branches, number of secondary branches, pod length, and percent oil content. GCA mean squares were highly significant, while SCA mean squares were significant for plant height and length of main shoot. Both GCA and SCA mean squares were significant for seed yield per plant. GCA mean squares were significant for biological yield and harvest index, while SCA mean squares were highly significant for these traits. Only GCA mean squares were significant for days to 90% maturity, number of seeds per pod and thousand seeds weight. Only SCA mean square was significant for number of pod per plant.

The mean squares for GCA were much larger than mean squares for SCA in all the traits except for number of secondary branches and harvest index. For the traits in which both GCA and SCA mean squares were significant, components due to GCA and SCA were computed and variance ratios were calculated accordingly. The variance ratio results are presented in Table 2. The results indicate that the variance ratio was greater than unity only for length of main shoot (1.49) and near to unity for percent oil content (0.97) whereas variance ratios for other traits were much lower than unity.

Table 1. Mean squares for yield and yield attributing traits from the combined analysis of variance in a 7x7 diallel cross of Ethiopian mustard (*Brassica carinata* A. Braun), 2009/2010 and 2010/2011.

Trait	Mean squares		
	Replication (2)	Genotype (27)	Error (54)
Days to 50% flowering	83.61*	606.01**	18.69
Days to 90% plants maturity	44.30	147.09**	18.93
Plant height (cm)	428.57	367.98**	150.19
Length of main shoot (cm)	57.07	373.14**	69.90
Number of primary branches	9.08*	10.63**	1.95
Number of secondary branches	74.01	151.51**	34.67
Number of pods per plant	37853.01**	24837.14**	6698.91
Pod length (cm)	0.01	0.11**	0.03
Number of seeds per pod	0.01	2.76**	1.51
Seed yield per plant (g)	64.89	40.01**	21.55
Thousand seeds weight (g)	0.43*	0.18*	0.12
Biological yield (g)	1653.77*	1118.38**	466.75
Harvesting index (%)	12.36	9.85**	3.08
Percent oil content (%)	0.87	5.52**	0.96

**, ** = Significant at 5% and 1% probability levels, respectively; Numbers in parenthesis indicates degree of freedom*

Table 2. Pooled general (GCA) and specific (SCA) combining ability mean squares and estimates of variance component ratios of GCA to SCA for yield and yield attributed traits in 7 x 7 diallel cross of Ethiopian mustard, 2009/2010 and 2010/2011.

Trait	Mean squares			Variance component due to		
	GCA (6)	SCA (21)	Error (54)	GCA	SCA	Variance ratio
DAF	1465.10**	360.56**	18.69	160.71	341.87	0.47
DAM	468.53**	55.26	18.93	-	-	-
PLH (cm)	631.10**	292.80*	150.19	68.7	142.61	0.48
LMS (cm)	1151.45**	150.77*	69.90	120.17	80.87	1.49
NPB	23.99**	6.82**	1.95	2.45	4.87	0.50
NSB	277.31**	129.85**	34.67	26.96	95.18	0.28
NPP	9006.99	29360.04**	6698.91	-	-	-
POL (cm)	0.192**	0.089**	0.027	0.018	0.062	0.29
NSP	4.22*	2.34	1.51	-	-	-
SYP (g)	52.15*	44.23*	21.55	3.4	22.68	0.15
TSW (g)	0.433**	0.11	0.12	-	-	-
BIOY (g)	1161.6*	1106.03**	466.75	77.21	639.28	0.12
HI (%)	7.604*	11.37**	3.08	0.50	8.29	0.06
Oil (%)	15.59**	2.64**	0.96	1.63	1.68	0.97

**, and **, Significant at 5% and 1% probability levels, respectively; Numbers in parenthesis indicate degree of freedom; **DAF = Days to 50% flowering; DAM = Days to 90% plants maturity; PLH = Plant height; LMS = Length of main shoot; NPB = Number of primary branches; TSW = Thousand seeds weight; BIOY = Biological yield; HI = Harvesting index; Oil = Oil content.*

3.1.2. General Combining Ability

Estimates of general combining ability (GCA) for yield and yield attributed traits of seven parental lines are presented in Table 3. The results showed that PBC-2005-1, Kiran (Early), Jayanti and Kiran (Bold) exhibiting positive and significant GCA effects for days to 50% flowering, while other three parents, HCO-288, HCO-211, and PBC-2006-4 recorded negative but non-significant GCA for this trait. On the other hand, Kiran (Early), PBC-2005-1, Jayanti, Kiran (Bold) and PBC-2006-4 had positive and significant GCA for days to 90% maturity. Two parents, Jayanti and Kiran (Early) had positive and significant GCA for plant height, while HCO-211 and Jayanti had same for length of main shoot.

Kiran (Early) and Jayanti showed positive and significant GCA for both primary and secondary branches, while PBC-2006-4 and HCO-288 registered positive and significant GCA only for number of primary and secondary branches, respectively. HCO-288 exhibited positive and significant GCA for both pod length and number of seeds per pod, whereas HCO-211 and Kiran (Early) only for pod length. HCO-288 and PBC-2005-1 had positive and significant GCA for thousand seeds weight.

None of the parents registered positive and significant GCA effects for seed yield per plant; biological yield and harvest index although four parents showed positive GCA for seed yield per plant, five parents for biological

yield and four parents for harvest index. Two parents viz. Kiran (Bold) and Kiran (Early) had positive and significant GCA for percent oil content.

3.1.3. Specific Combining Ability Effects

Pooled estimate of SCA over years of hybrids for yield and yield attributed traits are presented in Table 4. The results showed that 13 hybrids recorded positive SCA effects for plant height and number of secondary branches. Twelve out of 21 hybrids exhibited positive SCA for days to 50% flowering, length of main shoot, number of pod per plant, biological yield and percent oil content. Eleven hybrids registered positive SCA effects for number of primary branches. Ten out of 21 hybrids exhibited positive SCA for seed yield per plant and harvest index.

Ten hybrids exhibited negative and significant SCA effects for days to 50% flowering which was good specific combinations if early flowering and consequently early maturing is required. For this trait, four hybrids registered negative and highly significant SCA effects.

Two hybrids each for plant height and length of main shoot registered positive and significant SCA, while one hybrid exhibited negative and significant SCA effect for plant height. Four hybrids for number of primary branches and three hybrids for number of secondary branches recorded positive and significant SCA effects. Similarly, six hybrids revealed positive and significant SCA effects for number of pods per plant. On the other hand, only three hybrids had positive and significant SCA effects for pod length. One hybrid exhibited positive and significant SCA for harvest index, whereas three hybrids for seed yield per plant and five hybrids had the same for biological yield. But none of the hybrids was the best combination for percent oil.

Considering all the traits, negative SCA effects were recorded by all the hybrids for all the traits but not statistically significant except in case of one hybrid for plant height, number of primary branches, biological yield, harvest index and percent oil content. In case of days to 50% flowering, negative and significant SCA may imply good combination whenever earliness is an interest as the breeding objective.

3.2. Standard Heterosis

Standard heterosis (SH %) that were computed for 14 traits are given in Table 5. The minimum SH was registered for harvest index (-38.22%), while maximum (191.57%) was recorded for number of pods per plant (NPP). All the hybrids exhibited positive SH in desirable direction for NPP and length of main shoot (LMS). Twenty out of 21 hybrids displayed positive SH for plant height (PLH), number of secondary branches (NSB) and thousand seeds weight (TSW). More than 70% (15-18) of the hybrids registered negative SH for days to 50% flowering (DAF 50%), and positive SH for pod length (POL), seed yield per plant (SYP), and biological yield (BIOY). In addition, 12 out of 21 hybrids gave negative SH for days to 90% maturity in desired direction. Similarly, same number of hybrids exhibited positive SH for harvest index (HI). Less than 10 hybrids had positive SH for number of primary branches, seeds per pod and percent oil content. The mean SH of hybrids for all traits were positive or negative (DAF 50% and DAM 90%) in desired direction except for HI and oil content, which were negative in undesired direction.

At least one hybrid exhibited significant ($P < 0.01$) SH in the desired direction for PLH and 20 hybrids for TSW (Table 5). Five hybrids also displayed highly significant ($P < 0.01$) SH for seed yield per plant. These hybrids were: P4 x P6 (66.09%), P2 x P4 (62.159%), P5 x P7 (54.83%), P2 x P5 (45.93%) and P2 x P7 (42.82%). Moreover, these hybrids also displayed highly significant ($P < 0.01$) SH for 7 to 10 other traits. On the other hand, none of the hybrids displayed negative and significant SH for eight out of 14 studied traits except in case of percent oil content, where more than half of the hybrids showed negative and significant ($P < 0.05$) SH.

Table 3. Pooled estimates of general combining ability (GCA) effect for yield and yield attributed traits of seven parental lines in a diallel cross of *Brassica carinata* A. Braun, 2009/2010 and 2010/2011.

	GCA effect												
Parents	DAF	DAM	PLH (cm)	LMS (cm)	NPB	NSB	POL (cm)	NSP	SYP (g)	TSW (g)	BIOY (g)	HI (%)	Oil (%)
P1	-9.33**	-6.95**	-5.54**	11.99**	-1.52**	-4.69**	0.07*	0.12	-1.82	-0.11	-11.6	0.35	-0.81**
P2	-11.1**	-4.95**	-1.38	1.74	-0.48	2.20*	0.08*	0.75**	0.23	0.19**	5.34	-0.4	-0.89**
P3	7.22**	2.09**	0.75	-2.79	-0.63*	-3.47**	0.03	-0.18	-0.55	0.15*	-7.03	0.50	-0.13
P4	3.63**	1.94*	-5.74**	-4.89*	-0.04	0.87	-0.1*	0.08	0.37	-0.14	2.27	-0.11	0.02
P5	5.70**	3.90**	5.63**	-8.25**	0.89**	2.20*	0.07*	0.04	0.79	0.02	3.83	0.01	1.26**
P6	4.22**	2.09**	6.50**	2.97*	1.00**	2.42*	-0.1*	-0.44	-0.10	-0.07	3.05	-0.61	0.64**
P7	-0.37	1.90*	-0.22	-0.77	0.79**	0.46	-0.02	-0.37	1.08	-0.05	4.12	0.27	-0.09
SE (gi)	0.77	0.78	2.18	1.49	0.25	1.05	0.03	0.22	0.83	0.06	3.85	0.31	0.18
SE (gi-gj)	1.18	1.18	3.34	2.28	0.38	1.60	0.05	0.33	1.26	0.09	5.88	0.48	0.27

**, **, Significant at 5% and 1% probability levels, respectively; ** DAF = Days to 50% flowering; DAM = Days to 90% plants maturity; PLH = Plant height; LMS = Length of main shoot; NPB = Number of primary branches; NPP = Number of pods per plant; NSB = Number of secondary branches; POL = Pod length; NSP = Number of seed per pod; SYP = Seed yield per plant; TSW = Thousand seeds weight; BIOY = Biological yield; HI = Harvesting index; Oil = Percent oil content; ** P1 = HC)-211; P2 = HCO-288; P3 = PBC-2005-1; P4 = Kiran (Bold); P5 = Kiran (Early); P6 = Jayanti; P7 = PBC-2006-4.*

Table 4. Pooled estimates of specific combining ability (SCA) effects for yield and yield attributed traits of Ethiopian mustard (*Brassica carinata* A. Braun) hybrids grown 2009/2010 and 2010/2011.

	SCA effect										
Crosses	DAF	PLH (cm)	LMS (cm)	NPB	NSB	NPP	POL (cm)	SYP (g)	BIOY (g)	HI (%)	Oil (%)
P1 x P2	17.91**	-3.68	2.61	0.92	-4.29	-25.98	0.10	-2.44	-20.79	1.24	-2.95**
P1 x P3	-10.1**	9.12	5.73	0.40	6.71*	72.24	0.01	3.78	17.58	0.87	0.45
P1 x P4	-7.46**	5.95	11.71**	-0.19	-1.29	-4.80	-0.06	-1.88	-4.38	-1.11	0.52
P1 x P5	-8.87**	-8.43	-0.40	-0.12	0.38	-8.72	0.13	-0.87	3.39	-2.13	0.10
P1 x P6	-3.39	5.04	-0.26	0.77	0.49	87.02 *	0.09	4.36*	24.51*	0.04	0.55
P1 x P7	0.87	4.89	7.19	-0.34	2.12	62.43	-0.05	0.62	3.43	-0.02	-0.10
P2 x P3	-11.7**	3.43	-3.56	1.03	4.49	37.69	-0.09	-0.97	-3.68	-0.33	0.36
P2 x P4	-8.06**	12.99*	1.75	-0.57	3.82	111.32 **	0.04	6.23**	33.02**	0.24	-0.39
P2 x P5	-5.13**	11.54	1.03	1.84*	6.49*	93.72*	-0.04	3.45	11.47	1.04	-0.09
P2 x P6	-8.65**	-2.32	11.45**	-1.27	5.60	-71.56	0.27**	-4.51	12.25	-5.8**	0.04
P2 x P7	-2.39	5.06	6.29	0.29	3.57	63.87	0.21*	2.71	23.84*	-1.09	0.17
P3 x P4	7.32**	-7.28	-2.19	-0.42	-1.84	-60.80	-0.08	-4.41	-21.27	-0.55	-0.38
P3 x P5	3.57	-5.46	-1.10	-1.01	-4.51	-6.40	0.10	-2.20	-9.16	-0.15	0.002
P3 x P6	3.72	5.74	0.28	1.55*	1.94	74.02	0.07	1.51	3.62	0.87	0.95
P3 x P7	0.98	4.66	3.42	0.77	-0.44	34.09	-0.05	-2.61	-2.79	-1.96	0.48
P4 x P5	4.50**	-0.43	3.88	0.40	4.82	116.91**	-0.27	2.05	5.88	1.14	-0.69
P4 x P6	-1.69	1.97	-1.88	2.29**	11.60**	175.98 **	0.02	7.12**	25.32*	2.63**	-0.25
P4 x P7	-11.8**	-9.51	-2.01	-0.82	-0.10	-31.61	0.07	-3.25	-4.09	-2.26	-0.92
P5 x P6	7.57**	2.66	-8.26	-0.31	-1.07	-73.61	-0.12	-4.58	-18.24	-1.37	0.30
P5 x P7	-15.2**	22.11**	-5.71	3.58**	12.23**	120.13**	-0.04	3.89	22.69*	0.09	0.49
P6 x P7	-17**	-17.95**	8.40	-2.86**	-3.99	-52.13	0.29**	-4.95	-28.53*	0.52	-0.92
SE (Sij)	2.24	6.35	4.33	0.72	3.05	42.41	0.08	2.41	11.20	0.91	0.51
SE (Sij-Sik)	3.33	9.43	6.44	1.07	4.53	63.00	0.13	3.57	16.63	1.35	0.76
SE (Sij-Skl)	3.11	8.82	6.02	1.00	4.24	58.93	0.12	3.34	15.56	1.26	0.71

**, **, Significant at 5% and 1% probability levels, respectively; ** P1 = HCO-211; P2 = HCO-288; P3 = PBC-2005-1; P4 = Kiran (Bold); P5 = Kiran (Early; P6 = Jayanti; P7 = PBC-2006-4; ***DAF = Days to 50% flowering; PLH = Plant height; LM = Length of main shoot; NPB = Number of primary branches; NSB = Number of secondary branches; NPP = Number of pods per plant; POL = Pod length; SYP = Seed yield per plant; BIOY = Biological yield; HI = Harvesting index; Oil = Percent oil content.*

Table 5. Percent heterosis over the commercial cultivar for yield and yield attributes in 7 x 7 diallel cross of *Brassica carinata* (2009/2010 and 2010/2011).

Cross	DAF	DAM	PLH (cm)	LMS (cm)	NPB	NSB	NPP
P1 x P2	-18.37**	-7.01	1.39	77.2**	-9.09**	0.00	42.77
P1 x P3	-28.57**	-8.28*	9.01	73.8**	-18.2**	27.78**	93.98
P1 x P4	-29.59**	-8.28*	4.08	83.2**	-18.2**	5.56	76.51
P1 x P5	-28.57**	-8.28*	2.55	45.6**	-9.09**	22.22**	74.10
P1 x P6	-24.49**	-6.37	9.86	73.3**	0.00	27.78**	125.30
P1 x P7	-24.49**	-7.01	6.35	82.2**	-9.09**	22.22**	112.65
P2 x P3	-31.63**	-5.73	8.23	26.3**	0.00	55.56**	64.46
P2 x P4	-31.63**	-5.73	9.79	34.1**	-9.09**	72.22**	137.95*
P2 x P5	-26.53**	-5.73	14.86	19.1**	18.18**	94.44**	127.11
P2 x P6	-31.63**	-5.73	8.23	76.8**	-9.09**	94.44**	21.08
P2 x P7	-29.59**	-5.73	8.57	55.1**	9.09**	72.22**	104.82
P3 x P4	3.06	0.00	0.54	13.47	-9.09**	11.11*	26.51
P3 x P5	1.02	2.55	7.27	7.95	-9.09**	5.56	59.04
P3 x P6	0.00	2.55	13.43	38.6**	18.18**	38.89**	101.20
P3 x P7	-8.16	2.55	9.45	37.1**	9.09**	16.67**	79.52
P4 x P5	-2.04	3.18	6.53	14.9**	9.09**	77.78**	162.65*
P4 x P6	-9.18	3.82	8.29	28.2**	27.27**	116.67**	191.57**
P4 x P7	-24.49**	0.64	-1.09	18.8**	0.00	44.44**	68.67
P5 x P6	2.04	3.82	14.35	4.55	18.18**	55.56**	40.96
P5 x P7	-25.51**	3.82	20.84*	1.63	45.45**	116.67**	159.64*
P6 x P7	-29.59**	-4.46	0.85	63.2**	-9.09**	27.78**	49.40
Mean	-18.95	-2.64	7.78	41.7	2.16	47.88	91.42
CD (5%)	7.06	7.10	20.01	13.65	2.28	9.62	133.66
CD (1%)	9.39	9.45	26.62	18.15	3.03	12.79	177.76

**, **Significant at 5% and 1% probability levels, respectively; ** DAF = Days to 50% flowering; DAM = Days to 90% plants maturity; PLH = Plant height; LMS = Length of main shoot; NPB = Number of primary branches; NSB = Number of secondary branches; NPP = Number of pods per plant; POL = Pod length; ** P1 = HCO-211; P2 = HCO-288; P3 = PBC-2005-1; P4 = Kiran (Bold); P5 = Kiran (Early); P6 = Jayanti; P7 = PBC-2006-4.*

Table 5. Continued

Cross	POL (cm)	NSP	SYP (g)	TSW (g)	BIOY (g)	HI (%)	Oil (%)
P1 x P2	8.71**	7.14**	-12.78**	8.70**	-17.56	8.28**	-6.38**
P1 x P3	5.28**	0.00	24.79**	13.33**	14.28	11.41**	-3.62**
P1 x P4	-0.26	-7.14**	-7.87*	5.51**	-1.22	-3.53**	-3.07**
P1 x P5	9.50**	0.00	1.93	9.57**	10.20	-8.74**	-1.10
P1 x P6	3.43**	7.14**	31.84**	5.80**	35.09	0.23	-1.53
P1 x P7	2.37**	0.00	14.23**	2.61**	10.60	4.98**	-4.82**
P2 x P3	2.64**	-7.14**	6.15	26.09**	8.98	0.00	-4.03**
P2 x P4	2.37**	0.00	62.15**	19.71**	65.30**	-0.17	-5.47**
P2 x P5	5.01**	14.29**	45.93**	7.25**	40.81*	5.15**	-1.77*
P2 x P6	8.44**	0.00	-15.19**	17.97**	40.81*	-38.2**	-2.95**
P2 x P7	9.23**	0.00	42.82**	24.06**	56.32**	-5.67**	-4.24**
P3 x P4	-2.11**	7.14**	-16.64**	6.96**	-16.33	0.52	-3.62**
P3 x P5	7.65**	0.00	1.52	19.13**	0.40	3.53**	-1.65*
P3 x P6	1.85**	-7.14**	18.44**	18.84**	15.10	6.08**	1.06
P3 x P7	1.32**	-7.14**	0.69	6.96**	6.12	-5.44**	-1.82*
P4 x P5	-6.07**	-7.14**	37.22**	2.61**	30.19	7.53**	-1.03
P4 x P6	-3.17**	0.00	66.09**	-0.29	53.05**	12.57**	-1.46
P4 x P7	0.53**	7.14**	2.62	7.83**	18.37	-0.65**	-4.82**
P5 x P6	-2.11**	0.00	-11.88**	10.72**	1.63	-9.90**	2.83**
P5 x P7	2.64**	0.00	54.83**	8.70**	53.05**	3.65*	1.53
P6 x P7	6.33**	0.00	-12.36**	5.22**	-10.62	2.55	-24.5**
Mean	3.03	0.34	15.93	10.82	19.74	-0.76	-3.45
CD (5%)	0.28	2.01	7.58	0.57	35.28	2.87	1.57
CD (1%)	0.38	2.67	10.08	0.75	46.92	3.81	2.05

**, **Significant at 5% and 1% probability levels, respectively; **NSP = Number of seed per pod; SYP = Seed yield per plant; TSW = Thousand seeds weight; BIOY = Biological yield; HI = Harvesting index; Oil = Percent oil content; ** P1 = HCO-211; P2 = HCO-288; P3 = PBC-2005-1; P4 = Kiran (Bold); P5 = Kiran (Early); P6 = Jayanti; P7 = PBC-2006-4.*

4. Discussion

Both GCA and SCA mean squares were significant for days to 50% flowering, number of primary branches and secondary branches, pod length, percent oil content, plant height, length of main shoot, seed yield per plant, biological yield and harvest index. This suggested that the importance of both additive and non-additive gene actions in determining the expression of these characters. However, the primary importance of non-additive gene action was evident from the calculated variance ratios being less than unity except in case of length of main shoots.

On the basis of two years data, only GCA mean squares were significant for days to 90% maturity, number of seeds per pod and thousand seeds weight and only SCA mean square was significant for number of pod per plant. This result suggested that additive gene action was important for the expression of these traits (i.e., traits for which only GCA mean squares were significant). As indicated by various authors (Gardner, 1963; Sprague, 1966; Gravois and Mc New, 1993; Cukador Olmedo *et al.,* 1997), when GCA is only important, especially in self-pollinated crops, selection is the best breeding method to improve the characters in question. This is because additive effects are readily transmissible from one generation to another. Therefore, the traits like days to 90% maturity, number of seeds per pod and thousand seeds weight could be best improved through selection.

Earlier study on combining ability of *Brassica carinata* showed that mean squares of GCA were significant for all traits except secondary branches and pods per plant (Adefris and Becker, 2005) and mean squares of SCA were not significant in five traits (primary branches, plant height, days to maturity, seed yields and oil yields). The study has shown that for all traits with significant GCA and SCA mean squares, GCA variance was higher than SCA, and mostly GCA variance was more than triple the SCA variance component, and these suggested the primary importance of additive gene actions. In the present study, however, both GCA and SCA mean squares were significant for primary branches, plant height, days to maturity, seed yields, and oil content. The different results for these traits could be due to the difference in test materials and location (i.e., genotype, environment and their interaction). Other investigators in Rape seed and Indian mustard (Sabaghnia *et al,* 2010, Priti *et al.,* 2011, Sincik *et al*., 2011) also reported significant GCA and SCA mean squares for number of primary branches, plant height, harvest index, thousand seed weight, seed yield per plant, number of pod per plant and number of seed per pod.

Pooled GCA effects results showed that Kiran (Early) and Jayanti were good combiner for seven and six traits, respectively. Kiran (Early) was good combiner for days to 50% flowering, days to 90% maturity, plant height, number of primary branches and secondary branches, pod length and percent oil content. Jayanti was good combiner for days to 50% flowering, for days to 90% maturity, plant height, number of primary branches and secondary branches and oil content. Kiran (Early) was poor combiner for length of main shoot while Jayanti was poor combiner for length of main shoot and pod length. Followed these two parents, HCO-288 and PBC-2005-1 were good combiners each for three traits. HCO-288 was good combiner for pod length, number of seeds per pod and thousand seeds weight, while PBC-2005-1 was good combiner for days to 50% flowering, for days to 90% maturity and thousand seeds weight. However, HCO-288 was poor combiner for days to 50% flowering, for days to 90% maturity and oil content and PBC-2005-1 was poor combiner for primary and secondary branches.

The other three parents namely, HCO-211 was good combiner for length of main shoot and pod length, Kiran (Bold) was good combiner for days to 50% flowering and for days to 90% plants maturity and PBC-2006-4 was good combiner for days to 90% maturity and primary branches. In this study, HCO-211 was poor combiner as it had negative and significant GCA effects for six traits. In general, none of the parents were best combiner for seed yield per plant, biological yield and harvest index though HCO-288, Kiran (Bold), Kiran (Early) and PBC-2006-4 P7 were relatively good combiners for seed yield per plant.

Relatively 11 hybrids had negative and significant SCA effects for days to 50% flowering, implying good combinations for this trait in reducing days to flowering whenever earliness is required. Six and five hybrids were best combinations for pods per plant and biological yield, respectively. The same is true in four hybrids for number of secondary branches and three hybrids each for seed yield per plant, pod length, number of branches and length of main shoot. Only two hybrids were good combinations for plant height. None of the hybrids had positive and significant SCA effects for harvest index and oil content.

Considering individual hybrids, P4 x P6 was best specific combination, which exhibited positive and significant SCA effects for five traits namely, number of primary and secondary branches, number of pods per plant, seed yield per plant and biological yield. The second best specific combination was P5 x P7 that showed positive and significant SCA effects for five traits (plant height, primary branches, secondary branches, pods per plant and biological yield) and it had negative and significant SCA effect for days to 50% flowering that can be considered as good combination when earliness becomes a breeding objective. Similarly, P2 x P4 recorded positive and significant SCA effects for four traits (plant height, pods per plant, seed yield per plant and biological yield) and it displayed negative and significant SCA effect for days to 50% flowering. Two hybrids: P1 x P6 for pods per plant, seed yield per plant and biological yield and P2 x P5 for primary branches, secondary branches and pods per plant were good combinations. The later hybrid registered negative and significant SCA effect for days to 50% flowering. In short, the following hybrids were

noted good specific combinations: P4 x P5 for days to 50% flowering and pods per plant; P2 x P7 for pod length and biological yield; P2 x P6 for length of main shoot and pod length; P1 x P3 for number of secondary branches; P1 x P4 and P3 x P6 for length of main shoot (Table 4). Studies in Ethiopian mustard (Adefris and Becker, 2005), Rape seed (Sabaghnia *et al,* 2010; Sincik *et al*., 2011) and in Indian mustard (Priti *et al.,* 2011) identified also good combiner parents and good specific combinations.

The study indicated that hybrid vigour was important factor for increasing seed yield, and on the average, F_1s showed 15.93% higher yield than the mean of the commercial variety. For the two economic traits (seed and oil content), 15 and 1 out of 21 hybrids exceeded the yield of commercial variety, respectively. It has been observed that most of the hybrids (18 out of 21) failed to displayed positive SH for oil content. The average SH for oil content was virtually negative. Even though, three hybrids displayed positive SH, only one hybrid recorded highly significant oil content (P5 x P6, 2.83%). Negative or absence of heterosis for oil content is a common phenomenon in oil seed *Brassicas* (Banga and Labana, 1984; Brandle and McVetty, 1990; Schuler *et al*., 1992; Falk *et al.,* 1994; Adefris and Becker, 2005). Heterosis for oil content could be much appealing, but the available experience in *B. napus* indicates that it is not an essential prerequisite for the success of hybrids as far as oil yield per plant could maximized through higher yield.

5. Conclusion

Additive as well as non-additive gene actions were important in controlling the expression of days to 50% flowering, primary branches, secondary branches, pod length, oil content, plant height, length of main shoot, seed yield per plant, biological yield and harvest index. This suggested that selection followed by crossing is an appropriate breeding method to improve these traits. Additive gene action was important in controlling the expression of days to 90% maturity, seeds per pod and thousand seeds, implying selection could be the best method for improving them, while non-additive gene actions were important in controlling pods per plant, showing the importance of crossing to exploit its hybrid vigour. The level of heterosis in Ethiopian mustard was comparable to what were reported for other *Brassicas*, indicating a considerable potential to embark on hybrid breeding. Maximum SH (66.09%) for seed yield per plant indicates the potential of increasing seed yield by a systematic search for heterotic groups and testing parents for their combining ability. However, large-scale use of heterosis requires not only a sufficient level of heterosis but also the production of a large quantity of seed. The level of standard heterosis observed in this study could make heterosis breeding an attractive option for Ethiopian mustard yield improvement. However, the immediate exploitation of heterosis by developing hybrid varieties is limited because of the unavailability of suitable pollination control mechanisms (sterility systems) that ensure cross pollination.

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