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Genetic analysis of some agronomic traits in flax (*Linum usitatissimum* L.)

A.A. Mohammadi, G. Saeidi and A. Arzani

Department of Agronomy and Plant Breeding, College of Agriculture, Isfahan University of Technology, Isfahan, 84156-83111, Iran

***Corresponding author: aa.mohammadi@ag.iut.ac.ir**

Abstract

A complete diallel cross using eight flax genotypes including four Iranian breeding lines and four Canadian genotypes was carried out to estimate genetic parameters for days to flowering, days to maturity, plant height, primary branches per plant, number of capsules per plant, number of seeds per capsule, seed yield per plant, 1000-seed weight, seed yield and harvest index. Analysis of variances for the studied traits indicated highly significant differences among the genotypes. Significant general combining ability (GCA), specific combining ability (SCA) and reciprocal effects revealed meaningful contributions of additive, non-additive type of gene actions and maternal influence in governing the traits. The results showed that additive gene actions had greater effects on inheritance of days to flowering, days to maturity, plant height, primary branches per plant and 1000-seed weight. However, number of capsules per plant and number of seeds per capsule were largely controlled by dominance genetic effects, whereas both additive and non-additive gene actions were important in genetic control of harvest index, seed yield per plant and seed yield. The parental lines KH124, KO37, AH92 and SE65 exhibited positive and significant GCA effect on both seed yield per plant and seed yield. Parent KO37 also had the highest negative GCA for early flowering, early maturity and plant height. A considerable heterosis was also observed for the studied traits in some cross combinations and the highest heterobeltiosis values of 64.1, 35.2, 21.6, 77.2 and 91.3% were obtained for number of capsules per plant, number of seeds per capsule, 1000-seed weight, seed yield per plant and seed yield, respectively. These results imply the potential of producing superior cultivars through selection in segregating populations or heterosis breeding, providing that the technical problems hampering economical production of hybrid seeds in flax could be overcome.

Keywords: Diallel cross, Flax, General combining ability, Heterosis, Specific combining ability

Introduction

Flax (*Linum usitatissimum* L.) is one of the important species cultivated as an oil seed crop in some area of the world. Flaxseed is used for oil production and also in food industries because of its nutritional merits, essential poly unsaturated fatty acids such as alpha-linolenic acid and rich supply of soluble dietary fiber. Flaxseed oil is used as an industrial drying oil due to its high linolenic acid content (Green, 1986; Muir and Westcott, 2003). However, some flax genotypes have been developed which contain very low levels of linolenic acid in their oil, making them suitable for use as edible-oil (Green, 1986; Rowland, 1991). Knowledge of genetic behavior and type of gene action controlling target traits is a basic principle to design an appropriate breeding procedure for genetic improvement purposes. Hence, the success of any selection or hybridization breeding program depends on precise estimates of genetic variation components for the interested traits consisting of additive, dominance and non-allelic interaction effects (Jinks, 1983). The genetic improvement of seed yield and its components is one of the main objectives of flax breeding programs (Lay and Dybing, 1989). A number of genetic studies on quantitative traits of flax including yield components have been reported (Bhateria *et al.*, 2006; Kurt and Evans, 1996; Murty *et al.*, 1967; Patil and Chopde, 1981; Popescu *et al.*, 1999; Singh *et al.*, 2009; Sood *et al.*, 2007). The findings of Popescu *et al*. (1999) indicated the importance of general combining ability, underlining the additive gene effects in governing plant height, capsules per plant, seed weight and seed yield in flax. Other workers also found the significant additive gene action for most of the traits with the exception of non-additive genetic effects being significant for number of seeds per capsule, 1000-seed weight and biological yield (Sood *et al.*, 2007). However, Bhateria *et al*. (2006) found that both additive and non-additive (with predominance) gene actions significantly affected inheritance of seed yield and its related traits. Tyson (1989) observed that dominance gene action and maternal effects were contributed in genetic variation of seed weight in flax. Griffing's methods of diallel analysis have been widely used to provide reliable information on the nature and magnitude of gene effects that contribute to the expression of quantitative traits and to help plant breeders select appropriate parents for hybridization and producing desirable transgressive segregants (Griffing, 1956; Shattuck *et al.*, 1993). Realizing that a better understanding of the mode of inheritance of the traits leads to improve breeding strategies, the present study was conducted: 1) to estimate the genetic parameters and the mode of inheritance for yield components and some morphophysiological traits of flax in a set of complete diallel crosses, and 2) to identify superior parents for producing favorable progenies in the breeding program.

Materials and methods

Plant materials and experimental design

In this study, eight diverse genotypes were crossed in a complete diallel mating design. Four local flax breeding lines (KH124, KO37, AH92 and SE65) and four genotypes (McGregor, Flanders, CDC1774, and CDC1066) of Canadian origin were used as parents. The seeds of 64 entries (8 parents, 56 F_1 hybrids and their reciprocals) were sown in the field using a randomized complete block design with three replications on April 20, 2007. This experiment was carried out at the research farm of Isfahan University of Technology, Iran (51º 32´ E and 32º 32´ N, 1630 m asl). The soil at this site is silty clay loam, typic Haplargids of the arid tropic with pH = 7.5. Each plot consisted of three rows 30 cm apart and 120 cm long with plant to plant distances of 2 cm. The standard agronomic practices for flax were followed during the growing season. The plots were fertilized with 40 kg ha^{-1} P_2O_5 and 10 kg ha^{-1} N before sowing and 10 kg ha^{-1} N was top dressed at the branching stage. Days to flowering and days to maturity were recorded on plot basis, whereas plant height, primary branches per plant, number of capsules per plant, number of seeds per capsule, seed yield per plant (g), 1000-seed weight (g), and harvest index (%) were recorded using ten randomly selected plants from each plot. Seed yield was determined by harvesting plants from one meter lengths of the middle row in each plot. Analysis of variance (ANOVA) of data was performed using General Linear Model of SAS program and means comparisons were done using Fisher's least significant difference (LSD) test (Steel and Torri, 1984). For those traits showing significant variation among the entries, diallel analysis was performed to estimate general combining ability (GCA), specific combining ability (SCA) and reciprocal effects according to the Griffing's (1956) method 1, fixed model, using SAS program (Zhang *et al.*, 2005) based on the following statistical model: $X_{ijk} = m + g_i + g_j + s_{ij} + r_{ij} + e_{ijk}$. where, X_{ijk} is the observed value for a cross between the *i*th and *j*th parents in the *k*th replication; *m* is population mean; g_i and g_j are GCA values of the *i*th and *j*th parents, respectively; s_{ij} is the SCA value for the hybrid between the *i*th and the *j*th parents; r_{ij} is the reciprocal effect for the hybrid; and e_{ijk} is the residual. Percents of heterosis over the mid-parent (MP%) and better parent or heterobeltiosis (BP%) were calculated using the formulae [(value of F_1 - mean of parents)/(mean of parents) × 100] and [(value of F_1 - value of better parent)/(value of better parent) × 100], respectively (Fonseca and Patterson, 1968) . The critical differences (CD) for testing the significance of heterosis were calculated as follows:

CD (MP) = $\sqrt{3MSE/2r} \times t$ and CD (BP) = $\sqrt{2MSE/r} \times t$

Where, MSE is the mean squares of error, *r* is the number of replications, and *t* is the *t*-student value at 5 or 1% level of probability.

Results and discussion

Flowering and maturity

The ANOVA showed significant differences among the parents and also F_1 hybrids for both days to flowering and days to maturity (Tables 1 and 2). Days to flowering among the parents varied from 47 to 67 days belonged to KO37 and SE65, respectively (Table 1). SE65 and AH92 lines were late maturing parents while McGregor, Flanders, CDC1066 and KO37 were ranked as early maturing parents (Table 1). Significant ($P < 0.01$) mean squares of both general and specific combining abilities revealed the importance of both additive and non-additive gene effects for these two traits; however, high GCA($\hat{\phi}_g^2$)/SCA($\hat{\phi}_s^2$) ratios of 5.21 for days to flowering and 2.38 for days to maturity (Table 2) indicated the predominance of additive gene effects in their inheritance. High estimated broad-sense heritability for days to flowering (94.9%) and days to maturity (95.8%) also showed that these traits were under genetic control. These results indicate that effective selection for genetic improvement of these traits could be achieved through repeated selection of desirable recombinants from the segregating population. Our findings are in agreement with those of Kurt and Evans (1996) who reported the predominance of additive genetic effects for days to flowering but inconsistent with those of Singh *et al*. (2009) and Bhateria *et al*. (2006) who observed a greater variance of SCA than of GCA for both days to flowering and days to maturity. The highest positive GCA effect was observed for days to flowering and days to maturity in SE65 parent (4.85 and 7.97 days, respectively, Table 3). In contrast, the parent KO37 possessed the highest GCA effect for early flowering (-7.34 days) and early maturity (-5.07 days); thus, this parent could be used in recombination breeding for developing early maturing cultivars. The AH92 × SE65 hybrid had the highest and significantly positive SCA effects for days to flowering while the KH124 × SE65 hybrid showed the same SCA effects for days to maturity (Table 4). On the other hand, the highest negative and significant SCA effects of -2.62 were obtained for early flowering in the Flanders × KO37 cross and -6.51 for early maturity in the KO37 × SE65 cross. However, the reciprocal effect was significant and negative for days to flowering in the cross KO37 (male) × Flanders (female) (Table 5). Significant heterobeltiosis or heterosis over better parent for early flowering was observed in crosses between KO37 as the male parent and most others (McGregor, Flanders, CDC1774 and CDC1066) whereas their reciprocal crosses had negative and significant effects (Tables 5 and 6). All cross combinations between KO37 (as the male parent) and each of the others (as the female ones) also showed considerable heterosis over mid-parent for early flowering (Table 6). For early maturity, the hybrids of CDC1066 × McGregor, CDC1066 × Flanders and CDC1774 × CDC1066 and their reciprocal crosses presented significant heterobeltiosis for this trait (Table 6). Early flowering and maturity is one of the main objectives in breeding programs for flax (Kurt and Evans, 1996) and the present findings suggest the possibility of effective genetic improvement for early flowering and early maturity in these materials.

Plant height

Genotypes including parents and their hybrids varied significantly for plant height (Table 1). Among the parents, McGregor with 55.6 cm and KO37 with 28.0 cm had the highest and lowest plant heights, respectively. Analysis of variance for combining ability showed that GCA, SCA and reciprocal effects were significant for this trait (Table 2).

Table 1. Means of parents and their hybrids for measured characters in flax

Genotypes	DF	DM	PH (cm)	PB	YP (g)	CP	SC	SW (g)	SY (kg)	HI (%)
McGregor (1)	55.7	86.0	55.6	2.8	1.044	41.6	7.5	3.382	1353	32.5
Flanders (2)	56.0	86.7	48.1	3.3	1.065	40.5	6.7	3.942	1516	30.6
CDC1774 (3)	57.0	92.3	50.9	3.8	1.057	41.6	6.4	4.061	1592	24.3
CDC1066 (4)	57.7	86.7	45.8	3.1	0.389	28.3	4.3	3.118	583	16.8
KH124 (5)	57.7	94.3	41.4	5.5	1.538	46.5	7.4	4.409	2221	34.9
KO37 (6)	47.0	87.3	28.0	4.3	1.416	37.5	6.9	5.609	2368	36.3
AH92 (7)	61.3	110.3	52.0	7.0	1.024	40.0	5.0	5.136	1362	14.5
SE65 (8)	67.0	110.3	48.6	8.5	1.278	65.4	5.4	3.861	1161	17.2
1 × 2	56.3	88.7	50.2	3.6	1.042	36.3	7.7	3.733	1220	27.1
1 × 3	57.3	83.3	50.2	3.3	0.647	29.0	6.9	3.260	915	20.1
1 × 4	53.7	84.3	48.3	2.4	0.644	24.3	6.3	4.112	1032	27.7
1 × 5	55.7	84.3	41.2	4.6	1.697	62.8	6.4	4.250	1920	43.2
1 × 6	46.3	85.3	34.7	3.9	1.363	41.9	6.3	5.153	1702	38.4
1 × 7	58.7	94.7	55.8	5.5	1.752	63.5	7.8	4.061	2606	31.0
1 × 8	56.3	92.3	52.9	4.8	1.662	65.5	6.4	4.046	1852	30.1
2 × 1	56.7	90.3	48.7	3.6	0.981	57.2	6.3	2.783	929	27.3
2 × 3	56.0	85.0	47.3	4.3	1.088	39.2	7.9	3.641	911	32.4
2 × 4	55.3	84.3	47.4	3.6	0.893	37.6	6.8	3.303	1288	26.8
2 × 5	56.7	92.7	42.1	4.6	1.326	45.4	6.8	4.289	2342	34.7
2 × 6	46.3	85.0	34.1	3.9	1.644	47.4	7.3	4.771	2378	43.4
2 × 7	58.7	94.3	48.5	4.8	1.249	48.8	6.5	3.932	1297	29.6
2 × 8	58.3	98.3	53.1	5.1	1.327	47.2	7.0	4.063	2067	22.5
3 × 1	56.0	87.0	51.8	3.6	0.956	37.2	6.7	3.846	1193	25.1
3 × 2	54.7	88.7	47.8	4.0	1.279	47.3	6.4	4.177	1425	32.4
3 × 4	55.7	84.7	50.6	4.1	0.964	46.6	5.9	3.274	817	23.2
3 × 5	57.0	93.7	48.8	5.4	2.094	67.4	7.4	4.167	2625	37.1
3 × 6	50.7	86.7	34.5	4.2	1.171	33.1	6.8	5.162	1206	40.3
3 × 7	60.3	100.7	55.8	5.3	1.753	68.3	6.4	4.157	2371	29.0
3 × 8	62.3	98.3	52.9	5.9	1.520	61.4	6.0	4.237	1742	24.7
4 × 1	54.0	83.0	52.9	2.7	0.753	36.8	5.7	3.565	838	25.6
4 × 2	55.0	84.0	49.6	2.7	0.922	33.0	7.3	3.793	990	27.5
4 × 3	54.7	85.3	48.9	4.0	0.976	47.0	5.8	3.739	1121	27.4
4 × 5	55.7	91.0	42.8	3.8	1.166	37.7	7.2	4.289	1481	36.7
4 × 6	50.0	86.0	36.7	4.2	1.025	31.8	7.2	4.519	1700	31.7
4 × 7	60.3	94.0	50.0	5.4	1.203	44.3	6.8	4.008	928	23.1
4 × 8	59.3	98.7	52.7	4.6	1.357	57.0	6.1	3.851	1654	22.6
5 × 1	53.3	84.3	45.0	4.8	1.742	66.9	6.5	4.006	2101	36.8
5 × 2	55.3	86.3	41.6	4.3	1.485	46.2	7.6	4.235	2159	39.1
5 × 3	57.3	95.3	48.7	4.6	1.375	42.3	6.8	4.779	2205	30.8
5 × 4	54.7	86.7	48.6	4.5	1.765	58.4	7.0	4.365	1961	34.1
5 × 6	50.3	85.7	29.6	4.5	1.658	43.1	7.2	5.341	2542	39.4
5 × 7	60.3	96.3	49.4	6.7	2.103	61.8	7.2	4.755	2621	39.6
5 × 8	61.3	108.3	49.6	7.0	1.763	53.2	6.5	5.056	2183	26.1
6 × 1	43.7	84.3	36.1	3.8	1.513	40.0	6.8	5.502	1939	42.4
6 × 2	44.0	86.3	32.9	3.6	1.301	41.0	6.5	4.868	1724	37.8
6 × 3	44.3	87.7	35.2	4.4	1.811	62.1	6.2	4.581	1471	40.4
6 × 4	44.0	86.3	37.3	5.0	1.509	46.1	6.6	4.996	2093	36.0
6 × 5	51.3	87.3	33.1	4.6	1.448	38.4	7.3	5.224	2430	37.9
6 × 7	52.0	88.3	36.0	4.3	1.981	47.6	7.1	5.693	2874	52.8
6 × 8	54.7	89.3	34.9	4.5	2.094	54.8	7.8	4.940	2495	43.6
7 × 1	59.0	92.7	54.4	5.1	1.850	59.4	7.0	4.492	2431	31.0
7 × 2	57.7	93.7	53.1	4.8	1.752	56.7	6.7	4.608	2572	30.9
7 × 3	60.0	96.3	52.7	4.8	1.245	49.9	6.4	3.922	1357	22.5
7 × 4	59.7	93.3	54.7	5.1	1.320	53.7	6.2	4.076	1369	22.6
7 × 5	60.3	109.3	47.7	7.2	1.614	48.8	7.2	4.509	2283	27.5
7 × 6	51.3	87.3	34.4	5.1	1.867	43.9	7.7	5.523	2643	41.2
7 × 8	67.7	108.0	53.2	8.7	1.953	59.4	7.0	4.569	1634	21.8
8 × 1	58.0	93.3	53.0	4.6	1.683	54.9	6.9	4.463	2086	29.0
8 × 2	59.0	100.3	48.5	5.6	1.690	63.7	6.9	3.878	2146	31.1
8 × 3	60.0	90.7	49.9	5.1	1.619	59.0	6.6	4.096	2221	23.4
8 × 4	58.0	89.7	50.6	4.7	0.846	37.2	6.1	4.200	1195	20.3
8 × 5	61.3	111.0	48.1	7.5	1.622	47.0	7.4	4.681	1649	27.8
8 × 6	54.0	87.0	33.4	5.0	2.228	54.8	8.2	5.041	2931	43.2
8 × 7	67.7	110.0	51.7	7.2	1.243	44.1	6.1	4.637	1211	18.6
LSD (5%)	1.938	2.61	3.12	1.02	0.298	11.8	0.98	0.415	344	4.8

DF days to flowering, **DM** days to maturity, **PH** plant height, **PB** primary branches per plant, **CP** number of capsules per plant, **SC** number of seeds per capsule, **YP** seed yield per plant (g), **SW** 1000-seed weight, **SY** seed yield, **HI** harvest index

Table 2. Analysis of variance and quadratic components of GCA ($\hat{\phi}_g^2$), SCA ($\hat{\phi}_s^2$) and reciprocal ($\hat{\phi}_{rc}^2$) for measured characters in flax

Sources		MS									
	df	DF	DM	PH	PB	YP	CP	SC	SW	SY	HI
Rep	2	5.97*	10.27*	93.04**	0.27	0.45**	176.92*	0.30	0.15	978580.86**	43.90*
Entry	63	82.89**	180.58**	168.50**	5.06**	0.48**	354.53**	1.41**	1.22**	1073578.47**	187.71**
GCA	7	652.83**	1254.30**	1381.62**	37.62**	2.35**	1104.46**	4.00**	8.69**	5204035.74**	1088.91**
SCA	28	17.08**	68.35**	22.92**	1.51**	0.29**	271.23**	1.58**	0.32**	790843.13**	115.70**
REC	28	6.21**	24.39**	10.80**	0.46	0.19**	250.34**	0.60*	0.25**	323699.49**	34.42**
Error	126	1.44	2.61	3.73	0.40	0.03	53.84	0.37	0.07	45440.81	8.97
$\hat{\phi}_g^2$		13.57	26.08	28.71	0.78	0.05	21.89	0.08	0.18	107470.73	22.50
$\hat{\phi}_s^2$		2.61	10.96	3.20	0.19	0.04	36.23	0.20	0.04	124233.72	17.79
$\hat{\phi}_{rc}^2$		1.59	7.26	2.36	0.02	0.05	65.50	0.08	0.06	92752.89	8.48
$\hat{\phi}_g^2 / \hat{\phi}_s^2$		5.21	2.38	8.98	4.18	1.11	0.60	0.37	4.18	0.87	1.26
h^2_b (%)		94.9	95.8	93.6	79.5	83.3	65.1	48.4	84.5	88.3	86.9

* ,** Significantly different from zero at 5% and 1% probability levels, respectively
DF days to flowering, **DM** days to maturity, **PH** plant height, **PB** primary branches per plant, **CP** number of capsules per plant, **SC** number of seeds per capsule, **YP** seed yield per plant (g), **SW** 1000-seed weight, **SY** seed yield, **HI** harvest index

However, the magnitude of GCA variance was several times greater than the SCA one as shown by the high ratio (8.98) of GCA/SCA estimate, which in turn indicated that the greatest amount of genetic variation for this trait was mainly due to the additive gene action. These results are in agreement with the findings of Sood *et al*. (2007), but inconsistent with those of Bhateria *et al*. (2006) who demonstrated that the non-additive effects were more important for the genetic control of plant height in flax. The high magnitude of broad-sense heritability (93.6%) and relative importance of fixable type of gene action for plant height implied the possibility of effective selection for genetic improvement of this trait and that the parents could be selected based on their GCA effects. Estimates for GCA effects showed that the parents KO37 and KH124 had significant and negative values (-12.33 and -2.31 cm, respectively), whereas AH92 and McGregor parents had the higher, positive and significant GCA values of 4.08 and 3.15 cm, respectively (Table 3). Both negative and positive SCA effects were observed among the hybrids and their reciprocals for plant height (Table 4). SCA effects for plant height varied from -3.75 to 2.52 cm, belonging to McGregor × KH124 and CDC1774 × KH124 hybrids, respectively (Table 4). Significant reciprocal effects in some crosses for plant height indicated the importance of maternal effects for this trait (Table 5). Considering the superiority of the parental lines KO37 and KH124 for seed yield and other agronomic traits despite their limitation of short plant height (28 and 41.4 cm respectively) in mechanical harvesting, it seems that the hybridization of these parents with McGregor which possessed a high GCA effect for plant height could lead to the development of superior recombinant lines for both plant height and other agronomic traits.

Primary branches per plant

Analysis of variance indicated that the entries effect was significant at 1% level of probability for primary branches per plant (Table 2). A range of 2.8 to 8.5 branches per plant observed for the parents McGregor and SE65, respectively, indicated a high variability among the parents. Significant mean squares of GCA and SCA (Table 2) revealed the importance of both additive and non-additive gene effects in genetic variation of primary branches per plant; however, the GCA/SCA ratio (4.18) confirmed the preponderance of additive genetic effects in its genetic control. These results were in agreement with earlier reports (Patil and Chopde, 1981; Sood *et al.*, 2007) but not with those of Singh *et al*. (2009) who reported a higher importance of non-additive gene actions on the genetic control of primary branches per plant. Estimations for combining ability effects showed positive and significant GCA values of 1.33 and 1.13 for the parents SE65 and AH92, respectively. However, the GCA effects for the parents McGregor, CDC1066, Flanders, KO37 and CDC1774 were significantly negative (Table 3). The hybrids CDC1066 × KO37, KH124 × SE65, KH124 × AH92 and their reciprocal crosses along with cross AH92 × SE65 showed high positive SCA effects for primary branches per plant (Table 4). The SCA effects ranged from -0.91 to +1.05 branches per plant obtained for the hybrids KO37 × SE65 and KO37 × CDC1066, respectively. No signify-cant heterobeltiosis was found for primary branches per plant. However, considerable and significant heterosis over mid-parent was found in the range -28.8 to 35.9 % in different crosses (Table 6). Since the parents AH92 and SE65 had higher GCA effects for branching and a good performance for seed yield, it seems that using these parents in recombination breeding programs may accumulate the genes responsible for branching in the recombinant inbred lines.

Seed yield and its components

Significant variations in seed yield and its components including number of capsules per plant, number of seeds per capsule, 1000- seed weight and seed yield per plant were observed among the parents and their F_1 hybrids (Table 1). Analysis of variance for combining ability showed that GCA, SCA and reciprocal effects significantly affected seed yield and its components (Table 2), implying that additive, non-additive and maternal effects influenced the inheritance of these traits.

Table 3. Estimates of general combining ability effects of parents for measured characters in flax

Parent	DF	DM	PH (cm)	PB	YP (g)	CP	SC	SW (g)	SY (kg)	HI (%)
McGregor (1)	-1.13**	-4.28**	3.15**	-0.87**	-0.123**	-0.55ns	0.06ns	-0.322**	-177**	0.36ns
Flanders (2)	-0.78**	-2.32**	0.33**	-0.68**	-0.139**	-2.48*	0.21*	-0.327**	-114**	0.62ns
CDC1774 (3)	0.30*	-1.28**	2.55**	-0.34**	-0.108**	0.34ns	-0.18*	-0.252**	-221**	-2.27**
CDC1066 (4)	-0.57**	-3.99**	1.68**	-0.79**	-0.389**	-7.47**	-0.51**	-0.429**	-542**	-4.69**
KH124 (5)	0.72**	2.03**	-2.31**	0.58**	0.225**	2.78**	0.35**	0.224**	414**	4.16**
KO37 (6)	-7.34**	-5.07**	-12.33**	-0.38**	0.194**	-4.17**	0.30**	0.834**	409**	9.20**
AH92 (7)	3.87**	6.95**	4.08**	1.13**	0.162**	3.90**	-0.10ns	0.252**	163**	-2.72**
SE65 (8)	4.85**	7.97**	2.85**	1.33**	0.177**	7.65**	-0.13ns	0.018	67*	-4.66**

* ,** Significantly different from zero at 5% and 1% probability levels, respectively
DF days to flowering, DM days to maturity, PH plant height, PB primary branches per plant, CP number of capsules per plant, SC number of seeds per capsule, YP seed yield per plant (g), SW 1000-seed weight, SY seed yield, HI harvest index

The low ratio of GCA/SCA for number of capsules per plant (0.60) and number of seeds per capsule (0.37) indicated that the role of non-additive gene effects was more important than the additive ones on the variations in these traits, a finding which agrees well with the results reported elsewhere (Bhateria *et al.*, 2006; Kurt and Evans, 1996; Singh *et al.*, 2009). The preponderance of non-additive gene effects implies that selection can be effective for improving the number of capsules per plant and number of seeds per capsule only if it is performed in later generations. Moderate estimates of broad-sense heritability of 65.1% for number of capsules per plant and 48.4% for number of seeds per capsule showed relatively high influence of environmental factors on phenotypic variation in these traits, which lead to a reduced efficiency of the selection program (Falconer and Mackay, 1996). High broad-sense heritability estimates for seed yield per plant (83.3%) and 1000-seed weight (84.5%) indicated that most of their phenotypic variation was due to genetic factors. Also the GCA/SCA ratio was more than unity for these traits (Table 2), showing the predominance of additive gene effects rather than non-additive ones in the expression of these traits. Therefore, their genetic improvement can be achieved through increasing frequency of favorable alleles by recurrent selection of desirable recombinants from the segregating population. In previous studies significant influence of both additive and non-additive genetic effects on the inheritance of seed weight and seed yield per plant was reported (Sood *et al.*, 2007) and the reported GCA variance was greater than the SCA for seed weight and seed yield per plant (Patil and Chopde, 1981). In the studies of Smith and Aksel (1974) and Tyson (1989), the reported GCA and reciprocal effects were significant for seed weight in flax. Regarding number of capsules per plant, significant differences were observed among the parents for this trait (Table 1) ranging from 28.3 to 65.4 capsules observed for CDC1066 and SE65, respectively. Estimates of combining ability for number of capsules per plant showed positive and significant GCA effects for SE65 and AH92, with the highest value of 7.65 for SE65 (Table 2). The SCA effects for number of capsules per plant ranging from 5.96 to 14.63 were high and significant in the hybrids McGregor × KH124 , McGregor × AH92, CDC1774 × AH92 and CDC1774 × CDC1066 with the highest observed for McGregor × KH124 (Table 4). Beneficial and significant heterosis over mid-parent and better parent for number of capsules per plant was observed in some crosses with the highest heterobeltiosis of 64.1% belonging to the hybrid CDC1774 × AH92 (Table 6). The estimates of combining ability showed that the GCA values for number of seeds per capsule was significant and positive for the parents KH124, Flanders and KO37 but negative for the parents CDC1066 and CDC1774 (Table 3). The highest SCA effect of 1.05 seeds per capsule was obtained for the hybrid KO37 × SE65; however, the lowest (-0.70 seeds per capsule) was observed in the hybrid McGregor × KH124. Some cross combinations exhibited considerable and significant heterosis over mid-parent and better parent (heterobeltiosis). The highest heterobeltiosis was 35.2% and belonged to the hybrid CDC1066 × AH92 (Table 6). A considerable variation was observed for 1000-seed weight among the parents and the highest (5.609 g) and the lowest (3.118 g) mean for this trait belonged to KO37 and CDC1066, respectively. Among the hybrids, a range of 2.783g to 5.693g was observed for 1000-seed weight (Table 1). The parents KO37, KH124 and AH92 had positive and significant GCA values for 1000-seed weight but the Canadian parents CDC1-066, Flanders, McGregor and CDC1774 showed significantly negative GCA effects (Table 2), indicating the superiority of the local genotypes over the Canadian ones for this trait. Positive and significant SCA effects were observed in some cross combinations (Table 4). The highest positive value of SCA was 0.491 g observed in cross McGregor × KO37 and the lowest value of -0.417g belonged to the hybrid McGregor × Flanders. However, the reciprocal effect was significantly negative for this cross (Table 5). Beneficial and significant heterosis over both mid-parent and better parent was found in some hybrids and the highest heterobeltiosis (21.6%) belonged to the cross combination of McGregor × CDC1066 (Table 6). The parental genotypes showed a high genetic variation for seed yield per plant and its means ranged from 0.389 g (for CDC1066) to 1.538 g (for KH124) (Table 1). Highly significant differences were also observed among the F_1 hybrids and the highest seed yield per plant was obtained for the hybrid KO37 × SE65 and its reciprocal (Table 1). Based on the estimates of GCA effects, the local parental genotypes KH124, KO37, SE65

Table 4. Estimates of specific combining ability effects for measured characters in flax

Cross	DF	DM	PH (cm)	PB	YP (g)	CP	SC	SW (g)	SY (kg)	HI (%)
1 × 2	2.51**	4.32**	-0.03	0.39	-0.123	1.80	0.01	-0.417**	-402**	-4.65**
1 × 3	1.53**	-1.05	-0.69	-0.07	-0.364**	-14.67**	0.16	-0.198*	-316**	-6.37**
1 × 4	-0.37	0.16	-0.22	-0.51*	-0.187*	-9.42**	-0.27	0.265**	-114	0.11
1 × 5	-0.99*	-5.20**	-3.75**	0.24	0.222**	14.63**	-0.70**	-0.098	3	4.57**
1 × 6	-2.43**	2.41**	-1.41	0.36	-0.030	-2.30	-0.50*	0.491**	-181*	-0.03
1 × 7	0.19	-0.78	1.91*	0.29	0.365**	10.10**	0.69**	0.022	763**	2.49*
1 × 8	-2.45**	-2.64**	0.93	-0.50*	0.223**	5.15	0.00	0.234*	309**	2.98**
2 × 3	-0.16	-1.34*	-1.34	0.39	0.034	-2.61	0.41	0.163	-265**	3.20**
2 × 4	0.61	-1.30*	0.51	-0.12	0.039	-2.73	0.61**	-0.021	26	0.36
2 × 5	0.15	-1.99**	-2.16**	-0.20	-0.076	-2.46	-0.11	0.041	181*	1.24
2 × 6	-2.62**	1.28*	-0.47	0.09	0.021	2.89	-0.35	-0.012	-14	-0.10
2 × 7	-0.83	-2.41**	0.36	-0.43	0.081	3.36	-0.25	0.021	115	1.49
2 × 8	-1.31**	1.91**	1.64*	-0.06	0.075	2.30	0.15	-0.045	383**	-0.05
3 × 4	-0.54	-1.51*	-0.46	0.43	0.070	5.96*	-0.18	-0.137	-36	1.38
3 × 5	0.17	1.97**	2.52**	0.01	0.221**	3.74	0.22	0.177	452**	1.20
3 × 6	-1.43**	1.74**	-1.39	0.27	0.008	3.45	-0.40	-0.035	-618**	2.57*
3 × 7	0.03	1.05	1.61	-0.49*	0.049	6.90*	-0.04	-0.285**	153	-0.10
3 × 8	0.05	-3.97**	-0.01	-0.27	0.105	4.23	-0.16	0.075	366**	0.13
4 × 5	-0.89*	-0.99	0.33	-0.37	0.233**	4.75	0.51*	0.208*	79	5.05**
4 × 6	-0.99*	3.45**	1.63*	1.05**	0.065	2.64	0.35	0.028	259**	-1.53
4 × 7	0.80	-1.07	0.60	0.20	0.092	4.60	0.37	-0.106	-241**	-0.61
4 × 8	-1.52**	-1.59**	1.14	-0.65**	-0.083	-1.07	-0.02	0.111	129	-0.08
5 × 6	1.55**	-2.24**	-0.03	-0.38	-0.262**	-5.88*	-0.13	-0.100	-107	-5.57**
5 × 7	-0.16	2.07**	0.78	0.48*	0.075	0.59	0.21	-0.167	104	1.23
5 × 8	-0.14	7.89**	2.33**	0.60*	-0.105	-8.30**	0.00	0.302**	-335**	-3.41**
6 × 7	-0.77	-5.82**	-2.57**	-0.77**	0.171*	-1.96	0.48*	0.198*	416**	9.66**
6 × 8	0.92*	-6.51**	-2.39**	-0.91**	0.394**	3.36	1.05**	-0.186*	466**	8.01**
7 × 8	3.05**	2.30**	-0.49	0.73**	-0.137	-7.81**	0.06	0.009	-577**	-3.25**

DF days to flowering, **DM** days to maturity, **PH** plant height, **PB** primary branches per plant, **CP** number of capsules per plant, **SC** number of seeds per capsule, **YP** seed yield per plant (g), **SW** 1000-seed weight, **SY** seed yield, **HI** harvest index

* ,** Significantly different from zero at 5% and 1% probability levels, respectively

and AH92 had a high positive and significant general combining ability (Table 3), indicating that they could be used as good combiners for recombinant breeding programs. The SCA effects of the hybrids for seed yield per plant were significantly different and high SCA values of 0.394 and 0.365 g were obtained for KO37 × SE65 and McGregor × AH92, respectively (Table 4); however, the lowest SCA effect was -0.364 belonging to the cross McGregor × CDC1774. The desirable and significant heterosis in most crosses in this study confirms the results of Shehata and Comstock (1971). The highest heterobeltiosis of 77.2% was obtained for the cross combination AH92 × McGregor with no reciprocal effect (Tables 5 and 6). For seed yield which is the most important economic trait, there was a high variation among both the parents and their F_1 hybrids (Table 1). Parent KO37 followed by KH124 with 2368 and 2221 kg ha^{-1}, respectively, had considerably higher seed yields than the other parents, but the lowest mean of seed yield (583 kg ha^{-1}) was observed in parent CDC1066. Among the F_1 hybrids, the crosses of SE65 × KO37 and KO37 × AH92 with 2931 and 2874 kg ha^{-1}, respectively, displayed a far better performance than the others (Table 1). The estimate of GCA/SCA ratio for seed yield (0.87) confirmed the importance of both additive and non-additive gene actions in governing this trait. Popescu *et al*. (1999) also reported that both additive and non-additive genetic effects with additive ones being prevalent were important in genetic control of seed yield. The estimated value of high broad-sense heritability for seed yield (88.3%, Table 2), indicating a higher contribution by the genetic factors to phenotypic variation in seed yield, was consistent with the results obtained by Popescu *et al*.(1999). Based on the GCA effects, the parents KH124, KO37, AH92 and SE65 had significantly positive general combining ability effect for seed yield (Table 3). Therefore, these parents could be used in future breeding program. A significant SCA effect for seed yield was observed in some crosses and ranged from -618 kg in the cross CDC1774 × KO37 to 763 kg in the cross

Table 5. Estimates of reciprocal effect in the F_1 generation for measured characters

Cross	DF	DM	PH (cm)	PB	YP (g)	CP	SC	SW (g)	SY (kg)	HI (%)
1 × 2	-0.17	-0.83	0.75	0.00	0.031	-10.42**	0.69**	0.475**	145	-0.11
1 × 3	0.67	-1.83**	-0.83	-0.19	-0.154	-4.09	0.08	-0.293**	-139	-2.52*
1 × 4	-0.17	0.67	-2.31*	-0.17	-0.054	-6.27	0.29	0.274*	97	1.02
1 × 5	1.17*	0.00	-1.91	-0.08	-0.022	-2.05	-0.07	0.122	-90	3.20*
1 × 6	1.33**	0.50	-0.72	0.05	-0.075	0.95	-0.25	-0.174	-118	-1.97
1 × 7	-0.17	1.00	0.71	0.18	-0.049	2.08	0.40	-0.215*	87	0.03
1 × 8	-0.83	-0.50	-0.01	0.10	-0.010	5.28	-0.23	-0.208	-116	0.52
2 × 3	0.67	-1.83**	-0.27	0.15	-0.095	-4.07	0.74**	-0.268*	-256*	-0.02
2 × 4	0.17	0.17	-1.08	0.47	-0.015	2.27	-0.23	-0.245*	149	-0.33
2 × 5	0.67	3.17**	0.26	0.14	-0.080	-0.39	-0.39	0.027	91	-2.17
2 × 6	1.17*	-0.67	0.60	0.16	0.171*	3.19	0.44	-0.048	327**	2.83*
2 × 7	0.50	0.33	-2.29*	0.00	-0.252**	-3.95	-0.12	-0.338**	-637**	-0.67
2 × 8	-0.33	-1.00	2.31*	-0.23	-0.182*	-8.29**	0.08	0.092	-39	-4.30**
3 × 4	0.50	-0.33	0.88	0.08	-0.006	-0.17	0.04	-0.232*	-152	-2.09
3 × 5	-0.17	-0.83	0.07	0.41	0.359**	12.51**	0.29	-0.306**	210*	3.14*
3 × 6	3.17**	-0.50	-0.33	-0.14	-0.320**	-14.48**	0.30	0.291**	-132	-0.07
3 × 7	0.17	2.17**	1.57	0.28	0.254**	9.23**	-0.02	0.118	506**	3.26*
3 × 8	1.17*	3.83**	1.48	0.40	-0.050	1.20	-0.30	0.071	-239 *	0.62
4 × 5	0.50	2.17**	-2.88**	-0.39	-0.299**	-10.35**	0.11	-0.038	-240*	1.29
4 × 6	3.00**	-0.17	-0.29	-0.40	-0.242**	-7.16*	0.32	-0.239*	-196	-2.14
4 × 7	0.33	0.33	-2.38*	0.15	-0.058	-4.71	0.26	-0.034	-220*	0.29
4 × 8	0.67	4.50**	1.07	-0.03	0.256**	9.86**	-0.03	-0.175	229*	1.13
5 × 6	-0.50	-0.83	-1.77	-0.07	0.105	2.35	-0.04	0.058	56	0.73
5 × 7	0.00	-6.50**	0.89	-0.23	0.245**	6.51*	-0.01	0.123	169	6.08**
5 × 8	0.00	-1.33	0.77	-0.25	0.071	3.07	-0.42	0.188	267**	-0.83
6 × 7	0.33	0.50	0.78	-0.41	0.057	1.89	-0.32	0.085	115	5.78**
6 × 8	0.33	1.17	0.76	-0.25	-0.067	0.03	-0.20	-0.050	-217*	0.19
7 × 8	0.00	-1.00	0.73	0.77**	0.355**	7.66*	0.45	-0.034	211*	1.59

DF days to flowering, DM days to maturity, PH plant height, PB primary branches per plant, CP number of capsules per plant, SC number of seeds per capsule, YP seed yield per plant (g), SW 1000-seed weight, SY seed yield, HI harvest index

* ,** Significantly different from zero at 5% and 1% probability levels, respectively

between the two parents McGregor and AH92 (Table 4). A considerably high heterosis was obtained for seed yield in some crosses and superior heterobeltiosis was obtained in the hybrid McGregor × AH92 (91.3%) and its reciprocal cross (78.4%) followed by AH92 × Flanders (69.7%) and SE65 × McGregor (54.1%) crosses. Generally, most of the hybrids showing a high level of heterosis were those obtained from crossing between Canadian genotypes and Iranian breeding lines (Table 6).

Harvest index

Significant differences were observed for harvest index among the entries (Table 1). The analysis of variance for combining ability showed that both GCA and SCA effects were significant for this trait (Tables 2). The reciprocal effects were also significant for harvest index (Tables 2), which reflects the role of maternal effects in the expression of this trait (Kersay and Pooni, 1996). The GCA/SCA ratio for this character was 1.26, showing the importance of both additive and non-additive gene actions with the prevalence of additive effects in the genetic control of harvest index; however, Sood *et al.* (2007) in a triple test cross experiment in flax found that only the additive genetic effects were significant for this trait. Broad-sense heritability of 89.6% for harvest index indicated the lower contribution of non-genomic parameters to the variation of this trait in these materials. The highest value of GCA effect (9.20) for harvest index was obtained in parent KO37 which was considerably higher than those of the other parents (Table 3). The parent CDC1066, however, had the lowest value of GCA effect (-4.69%). The cross combination of KO37 × AH92 (with significant reciprocal effect) and KO37 × SE65 had more positive SCA effects than the others for harvest index (Tables 4 and 5). Significant heterosis was observed in some crosses and the highest value over the better parent (45.6%) and mid-parent (107.9%) obtained in the hybrid KO37 × AH92 (Table 6). Development of flax cultivars with a high harvest index is the breeder's major purpose (Kurt and Evans, 1996) and the high genetic variation for this trait in this study (Table 1) indicates the possibility for its improvement in flax breeding.

Table 6. Heterosis (%) over the mid parent (MP) and better parent (BP) for measured characters in flax

	DF		DM		PH		PB		YP		CP		SC		SW		SY		HI	
Cross	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP
1 × 2	0.9	1.2	2.7	3.1	-3.2	-9.7	16.8	7.4	-1.2	-2.2	-11.5	-12.7	8.7	3.0	1.9	-5.3	-14.9	-19.5	-14.1	-16.6
1 × 3	1.8	3.0	-6.5	-3.1	-5.7	-9.7	-1.0	-14.0	-38.4	-38.8	-30.3	-30.3	-1.0	-8.4	-12.4	-19.7	-37.9	-42.5	-29.4	-38.2
1 × 4	-5.3	-3.6	-2.3	-1.9	-4.7	-13.1	-19.1	-23.4	-10.2	-38.3	-30.6	-41.6	6.8	-15.6	26.5	21.6	6.6	-23.7	12.2	-14.9
1 × 5	-1.8	0.0	-6.5	-1.9	-15.0	-25.9	10.4	-16.9	31.5	10.4	42.6	35.1	-14.5	-14.7	9.1	-3.6	7.4	-13.5	28.1	23.7
1 × 6	-9.7	-1.4	-1.5	-0.8	-16.9	-37.6	10.4	-8.6	10.8	-3.8	6.1	0.8	-11.5	-15.2	14.6	-8.1	-8.5	-28.1	11.8	6.0
1 × 7	0.3	5.4	-3.6	10.1	3.9	0.5	11.6	-21.9	69.4	67.8	55.6	52.7	24.9	4.2	-4.6	-20.9	91.9	91.3	32.0	-4.5
1 × 8	-8.2	1.2	-5.9	7.4	1.7	-4.7	-14.8	-43.3	43.2	30.1	22.4	0.1	-0.1	-13.9	11.7	4.8	47.3	36.9	21.0	-7.5
2 × 1	1.5	1.8	4.6	5.0	-6.1	-12.3	16.5	7.2	-7.0	-7.9	39.3	37.4	-10.7	-15.4	-24.0	-29.4	-35.2	-38.7	-13.4	-15.9
2 × 3	-0.9	0.0	-5.0	-1.9	-4.5	-7.1	19.6	12.3	2.5	2.1	-4.6	-6.0	21.3	18.3	-9.0	-10.3	-41.3	-42.7	17.9	5.8
2 × 4	-2.6	-1.2	-2.7	-2.7	1.0	-1.5	12.4	9.0	22.7	-16.2	9.2	-7.1	23.6	1.9	-6.4	-16.2	22.8	-15.0	13.1	-12.4
2 × 5	-0.3	1.2	2.4	6.9	-5.9	-12.5	3.3	-17.2	1.9	-13.8	4.5	-2.2	-3.8	-8.6	2.7	-2.7	25.4	5.5	6.0	-0.5
2 × 6	-10.0	-1.4	-2.3	-1.9	-10.3	-29.1	3.7	-7.7	32.5	16.1	21.7	17.2	8.3	7.1	-0.1	-14.9	22.4	0.4	29.9	19.8
2 × 7	0.0	4.8	-4.2	8.8	-3.1	-6.7	-7.7	-31.9	19.5	17.2	21.3	20.6	10.8	-3.2	-13.4	-23.4	-9.9	-14.6	31.1	-3.3
2 × 8	-5.1	4.2	-0.2	13.5	9.9	9.4	-13.5	-39.7	13.2	3.8	-10.9	-27.9	16.5	5.2	4.1	3.1	54.4	36.4	-6.0	-26.6
3 × 1	-0.6	0.6	-2.4	1.2	-2.6	-6.7	10.4	-4.1	-9.0	-9.6	-10.6	-10.7	-3.2	-10.4	3.4	-5.3	-18.9	-25.0	-11.6	-22.7
3 × 2	-3.2	-2.4	-0.9	2.3	-3.4	-6.0	11.2	4.4	20.5	20.0	15.2	13.6	-1.5	-3.9	4.4	2.9	-8.3	-10.5	18.1	6.0
3 × 4	-2.9	-2.3	-5.4	-2.3	4.7	-0.4	19.2	8.8	33.3	-8.8	33.3	12.0	10.2	-7.3	-8.8	-19.4	-24.9	-48.7	12.7	-4.7
3 × 5	-0.6	0.0	0.4	1.4	5.9	-4.0	15.7	-2.4	61.3	36.1	52.9	44.9	7.4	-0.3	-1.6	-5.5	37.7	18.2	25.3	6.3
3 × 6	-2.6	7.8	-3.5	-0.8	-12.5	-32.2	3.2	-2.5	-5.3	-17.3	-16.3	-20.5	2.3	-1.3	6.8	-8.0	-39.1	-49.1	33.0	11.1
3 × 7	2.0	5.8	-0.7	9.0	8.6	7.4	-1.5	-24.0	68.4	65.8	67.4	64.1	12.5	0.4	-9.6	-19.1	60.5	48.9	49.4	19.3
3 × 8	0.5	9.4	-3.0	6.5	6.4	3.9	-4.3	-30.7	30.2	19.0	14.7	-6.2	1.4	-6.3	7.0	4.3	26.6	9.5	18.8	1.4
4 × 1	-4.7	-3.0	-3.9	-3.5	4.4	-4.7	-7.9	-12.8	5.0	-27.9	5.3	-11.5	-3.0	-23.3	9.7	5.4	-13.5	-38.1	4.0	-21.1
4 × 2	-3.2	-1.8	-3.1	-3.1	5.6	3.0	-17.0	-19.5	26.8	-13.4	-4.0	-18.4	31.9	8.7	7.4	-3.8	-5.7	-34.7	15.9	-10.2
4 × 3	-4.7	-4.1	-4.7	-1.5	1.1	-3.9	14.4	4.4	34.9	-7.7	34.3	12.8	8.8	-8.5	4.2	-7.9	3.1	-29.6	33.1	12.5
4 × 5	-3.5	-3.5	0.6	5.0	-1.8	-6.6	-12.9	-31.8	21.0	-24.2	0.8	-18.9	22.2	-3.2	14.0	-2.7	5.6	-33.3	41.9	5.1
4 × 6	-4.5	6.4	-1.1	-0.8	-0.6	-19.9	14.4	-0.8	13.5	-27.6	-3.2	-15.0	28.5	5.0	3.5	-19.4	15.2	-28.2	19.5	-12.6
4 × 7	1.4	4.6	-4.6	8.5	2.2	-3.8	7.2	-22.4	70.2	17.5	29.7	10.8	44.7	35.2	-2.9	-22.0	-4.6	-31.9	47.7	37.6
4 × 8	-4.8	2.9	0.2	13.8	11.7	8.6	-20.7	-45.7	62.8	6.2	21.5	-13.0	24.2	12.0	10.3	-0.3	89.6	42.4	32.6	31.0
5 × 1	-5.9	-4.2	-6.5	-1.9	-7.1	-19.0	14.4	-13.9	35.0	13.3	51.9	43.9	-12.6	-12.8	2.9	-9.1	17.6	-5.4	9.1	5.4
5 × 2	-2.6	-1.2	-4.6	-0.4	-7.1	-13.6	-3.0	-22.3	14.1	-3.4	6.3	-0.6	7.2	1.8	1.4	-3.9	15.6	-2.8	19.3	12.0
5 × 3	0.0	0.6	2.1	3.2	5.6	-4.3	-1.9	-17.3	6.0	-10.6	-3.9	-8.9	-1.0	-8.2	12.9	8.4	15.6	-0.7	4.1	-11.7
5 × 4	-5.2	-5.2	-4.2	0.0	11.4	6.0	4.9	-17.9	83.2	14.8	56.1	25.6	18.5	-6.2	16.0	-1.0	39.9	-11.7	31.9	-2.3
5 × 6	-3.8	7.1	-5.7	-1.9	-14.7	-28.5	-8.2	-18.7	12.3	7.8	2.6	-7.3	1.0	-3.0	6.6	-4.8	10.8	7.4	10.7	8.6
5 × 7	1.4	4.6	-5.9	2.1	6.0	-4.8	6.9	-4.3	64.2	36.8	42.8	32.9	15.6	-3.4	-0.4	-7.4	46.3	18.0	60.4	13.6
5 × 8	-1.6	6.4	5.9	14.8	10.4	2.2	0.0	-17.3	25.2	14.6	-5.0	-18.7	1.9	-12.1	22.3	14.7	29.1	-1.7	0.3	-25.1
6 × 1	-14.9	-7.1	-2.7	-1.9	-13.5	-35.0	7.8	-10.7	23.0	6.8	1.2	-3.8	-4.5	-8.5	22.4	-1.9	4.2	-18.1	23.3	16.8
6 × 2	-14.6	-6.4	-0.8	-0.4	-13.5	-31.6	-4.7	-15.1	4.9	-8.1	5.3	1.4	-4.7	-5.8	1.9	-13.2	-11.2	-27.2	12.9	4.2

Table 6. Continued

Cross	DF		DM		PH		PB		YP		CP		SC		SW		SY		HI	
	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP
6 × 3	-14.7	-5.7	-2.4	0.4	-10.8	-30.9	10.2	4.2	46.4	27.9	57.0	49.1	-6.8	-10.1	-5.2	-18.3	-25.7	-37.9	33.4	11.5
6 × 4	-15.9	-6.4	-0.8	-0.4	1.0	-18.7	35.9	17.8	67.2	6.5	40.3	23.2	17.1	-4.4	14.5	-10.9	41.8	-11.6	35.6	-0.8
6 × 5	-1.9	9.2	-3.9	0.0	-4.5	-20.0	-5.4	-16.3	-1.9	-5.8	-8.6	-17.4	2.2	-1.9	4.3	-6.9	5.9	2.6	6.6	4.6
6 × 7	-4.0	10.6	-10.6	1.1	-10.0	-30.8	-23.3	-38.3	62.3	39.8	23.0	19.1	19.7	3.5	6.0	1.5	54.1	21.4	107.9	45.6
6 × 8	-4.1	16.3	-9.6	2.3	-8.8	-28.1	-28.8	-46.5	55.5	47.9	6.6	-16.2	26.5	13.1	4.3	-11.9	41.4	5.4	63.1	20.3
7 × 1	0.9	6.0	-5.6	7.8	1.3	-2.0	4.1	-27.1	78.9	77.2	45.5	42.7	12.0	-6.6	5.5	-12.5	79.0	78.4	31.7	-4.7
7 × 2	-1.7	3.0	-4.9	8.1	6.0	2.1	-7.7	-31.9	67.7	64.5	40.9	40.1	14.8	0.2	1.5	-10.3	78.7	69.7	37.0	1.0
7 × 3	1.4	5.3	-4.9	4.3	2.4	1.4	-11.7	-31.9	19.7	17.8	22.2	19.8	13.2	1.0	-14.7	-23.6	-8.1	-14.7	15.9	-7.5
7 × 4	0.3	3.5	-5.2	7.7	11.9	5.3	1.3	-26.7	86.7	28.8	57.2	34.3	33.5	24.7	-1.2	-20.6	40.8	0.5	44.0	34.2
7 × 5	1.4	4.6	6.8	15.9	2.1	-8.3	14.4	2.4	26.0	4.9	12.7	4.9	15.9	-3.1	-5.5	-12.2	27.4	2.8	11.1	-21.3
7 × 6	-5.2	9.2	-11.6	0.0	-13.9	-33.8	-8.9	-26.7	53.0	31.8	13.3	9.6	30.4	12.8	2.8	-1.5	41.7	11.6	62.4	13.7
7 × 8	5.5	10.3	-2.1	-2.1	5.8	2.3	12.5	2.8	69.7	52.9	12.6	-9.2	34.9	29.9	1.6	-11.0	29.5	19.9	37.5	26.7
8 × 1	-5.4	4.2	-4.9	8.5	1.7	-4.7	-18.3	-45.7	45.0	31.7	2.7	-16.0	7.1	-7.8	23.2	15.6	65.9	54.1	16.8	-10.6
8 × 2	-4.1	5.4	1.9	15.8	0.3	-0.1	-5.6	-34.3	44.3	32.3	20.4	-2.6	13.7	2.7	-0.6	-1.6	60.3	41.6	30.0	1.5
8 × 3	-3.2	5.3	-10.5	-1.8	0.4	-1.9	-17.4	-40.2	38.7	26.7	10.2	-9.8	11.5	3.0	3.4	0.9	61.4	39.5	12.8	-3.7
8 × 4	-7.0	0.6	-9.0	3.5	7.2	4.2	-19.6	-44.9	1.4	-33.8	-20.6	-43.1	25.2	13.0	20.3	8.8	37.0	2.9	19.3	17.9
8 × 5	-1.6	6.4	8.5	17.7	7.0	-0.9	7.1	-11.4	15.2	5.4	-15.9	-28.1	15.0	-0.8	13.2	6.2	-2.5	-25.8	6.7	-20.4
8 × 6	-5.3	14.9	-12.0	-0.4	-12.8	-31.3	-20.9	-40.6	65.4	57.3	6.5	-16.3	33.1	19.0	6.5	-10.1	66.1	23.8	61.7	19.2
8 × 7	5.5	10.3	-0.3	-0.3	2.9	-0.5	-7.3	-15.4	8.0	-2.7	-16.4	-32.7	17.5	13.1	3.1	-9.7	-4.0	-11.1	17.5	8.3
CD (5%)	1.19	1.37	1.60	1.85	1.92	2.21	0.62	0.72	0.17	0.19	7.29	8.42	0.60	0.69	0.26	0.30	212.0	244.8	2.97	3.43

DF days to flowering, **DM** days to maturity, **PH** plant height, **PB** primary branches per plant, **CP** number of capsules per plant, **SC** number of seeds per capsule, **YP** seed yield per plant (g), **SW** 1000-seed weight, **SY** seed yield, **HI** harvest index

Conclusion

Overall, significant genetic variations were observed for the traits investigated in this study. Significant GCA and SCA effects for the studied traits imply the role of both additive and non-additive gene actions in the genetic control of all the studied traits. The ratios of GCA/SCA imply the higher contribution of additive gene effects to the inheritance of days to flowering, days to maturity, plant height, primary branches per plant, 1000-seed weight and harvest index. The preponderance of additive gene action in explaining genetic variations in these characters indicates the possibility for their genetic improvement through accumulating favorable alleles from parents with high GCA values in the target genotype using appropriate methods such as diallel selective mating or recurent selection. In addition to selection methods, hybrid vigor or heterosis in hybrid cultivar development could be exploited for the traits like number of capsules per plant, number of seeds per capsule, seed yield per plant and seed yield which non-additive genetic effects had a great impact on their genetic variation. However, due to the autogamus nature of flax, there are some technical problems associated with the economical production of hybrid seeds in this crop. GCA estimates showed that no any parent was a good combiner for all of the traits studied. Good combiner parents included McGregor for plant height, KO37 for early maturity and 1000-seed weight, KH124 for number of seeds per capsule, seed yield per plant and seed yield, SE65 for number of capsules per plant, and AH92 for primary branches per plant. Since genetic improvement of seed yield and its components is a major goal of any flax breeding program, these genotypes can be used in recombination breeding programs to accumulate their favorable genes responsible for increasing seed yield in promising pure lines.

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