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Study on genetic combining ability estimates for yield and related traits in linseed (*Linum usitatissiumu* L.)

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Abstract

Combining ability studies helps in selection of appropriate parents for a cross and also indicates suitable breeding procedure for handling a cross to develop a cultivar. In the present investigation, combining ability estimates for yield and related traits have been analyzed in 45 F_1 and 45 F_2 progenies derived from 10 parent half diallel mating design. The analysis of variances showed highly significant differences among the genotypes for all the traits studied. Significant differences have been found for general combining ability (GCA) effects among the parents as well as specific combining ability (SCA) effects among the hybrids for all the studied traits. The GCA and SCA components of variance were significant for all the traits. However, the magnitude of GCA variance was higher than SCA suggested the preponderance of additive gene action for most of the traits. The GCA:SCA ratio revealed predominance of additive gene effects in both the generations except seed weight in F_1 and husk weight and oil content in F_2 generation. Among all the parents, EC-1392, JLS-9 and JWR-17 were the best general combiners for branches/plant, capsules/plant and seeds/capsule and average to high combiners for other traits in both the generations. Most of the specific crosses for yield related traits as well as oil content involved high/average, average/average and average/poor general combiners. These crosses combinations could be utilized for further use in breeding program in combination with the parents having good general combining ability for improvement in yield of linseed.

Key words: Linseed, general combining ability, additive gene action, oil content, linolenic acid.

Introduction

Linseed (*Linum usitatissimum* L., 2n=2x=30) is a member of genus *Linum* within the family Linaceae with 14 genera and over 200 species. Out of those only *Linum usitatissimum* L. possess both agronomic and economic properties and are being exploited for both industrial and human consumption purposes. The linseed is reported to be of Indian origin and was first domesticated in the area of Middle East, south of the Taurus Mountains, Mesopotamia and ancient Egypt. It is one of the oldest crops grown for its seed and fibre and cultivated in over 2.6 million hectare with production of 614,000 metric tons in the year 2013-14 (FAOSTAT, 2014). Canada is the world's largest producer of linseed accounting for almost 80% of the worldwide trade followed by China, United States and India (FAOSTAT 2014). Linseed oil is considered to be the most widely available botanical source of Omega-3 among all the plants. Alpha-linolenic acid (ALA), an important Omega-3 fatty acid, constitutes upto 65% of total fatty acid composition in linseed oil (Worku et al., 2015). ALA has anti-inflammatory properties and has significant effects on inflammatory and autoimmune diseases including coronary heart disease, major depression, aging, rheumatoid arthritis, Chrohn's disease and cancer (Simopoulos, 2002). Linseed oil also possesses superior drying qualities due to high linolenic acid content which render it as an indispensable ingredient in paint and varnish, and in the manufacture of linoleum, oilcloth, printer's ink, patent leather, and a few other products. However, low Linolenic acid containing cultivars of flax have been also developed which are directly used as edible oil (Green, 1986; Rowland, 1995). Linseed oil cakes too have very good nutritive feeding value for animals (Bibi et al., 2015).The flax stem yields fibre of good quality having high strength, non-elasticity, repeated flexibility, a low density etc which make it very attractive and suitable use as a rope and thread (Jhala and Hall, 2010) that can be easily blended with cotton, hemp and jute to enhances its textiles properties (Chauhan et al., 2009). Besides oil and fibre, lignin is another major compound obtained through linseed which acts as antioxidant for humans. Flax seed contains 800 times higher lignans than other plant seeds except sesame (Jhala and Hall, 2010).

Linseed is a highly self-pollinated crop and the scope for exploitation of hybrid vigour will depend upon the type of gene action involved. Gene action refers to the behavior or mode of expression of genes in a genetic population. Knowledge of gene action helps in the selection of parents for use in the hybridization programs and also in the choice of appropriate breeding procedure for the improvement of various quantitative characters. Hence, insight into the nature of gene actions involved in the gene expression of various quantitative characters is essential to a plant breeder for starting a judicious breeding program. Gene action is usually measured in terms of components of genetic variances or combining ability variances effects. The general combining ability is primarily a function of additive and additive x additive genetic variance and used to designate the average performance of a line in hybrid combinations. On the other hand, specific combining ability is mainly a function of non-additive genetic variances and represents the performance of a line in a specific cross. Popescu et al. (1999) indicated the importance of general combining ability, underlying the additive gene effects in governing plant height, capsules/plant, seed weight/plant and seed yield in flax. However, Bhateria et al. (2006) found that both additive and non-additive (with predominance) gene actions significantly affected the inheritance of seed yield and its related traits. Griffing's (1956) method of diallel analysis provide reliable information on the nature and magnitude of gene effects that contributes to the expression of various traits and helps plant breeder to select appropriate parents for hybridization and producing desirable transgressive segregants. Genetic improvement of quantitative traits is a continuous process and informations requires on various genetical parameters of each experimental setup to accumulate desirable alleles for improved varieties. The genetical inferences obtained from one set of experimental material cannot be implemented to other set of experimental material with high accuracy (Yadav and Singh 2011). It was therefore essential to evaluate some more lines for their various genetic parameters related to yield and its component traits in linseed. Thus, the present investigation was undertaken to study the general combining ability and mode of gene action for various important traits in linseed.

Result and Discussion

Analysis of variance

Analysis of variance for the studied characters in the present experiment revealed significant differences among the parents, F_1 and F_2 progenies indicating considerable amount of diversity in the experimental material. The differences between parents vs F_1 and parents vs F_2 were found significant except for plant height (parents vs F_2) which suggested the presence of wide genetic variability in the materials generated and evaluated. Earlier, significant differences among genotypes for different traits in linseed were also reported (Popescu et al., 1999; El-Haleem 2015; Abdel-Moneam, 2014). The estimates of variance for general and specific combining ability calculated for both F_1 and F_2 were found to be highly significant for all the traits (Table 2). This indicated the importance of both additive and non-additive gene effects. However, the magnitude of GCA variance was higher than SCA variances of respective traits in both the generations suggesting preponderance of additive gene action except for husk weight/plant and oil content in F_2. The present findings was in accordance with the results reported earlier by Singh et al. (2008) and Mohammadi et al. (2010) where additive genetic variance was noticed for various economic traits in linseed. The relative magnitude of the estimates of variances of components due to δ^2s and δ^2g suggests the major role of non-additive gene action for all the traits in F_1 and F_2 generations except for days of 50% flowering and plant height. Such type of variability could be exploited by bi-parental mating followed by recurrent selection for further genetic improvement (Singh and Singh 1981). Similar results were also reported previously by Srivastava et al. (2007) and Jadhav et al. (2011) in linseed. The magnitude of average degree of dominance or potence ratio $[(\delta^2 s/\delta^2 g)^{0.5}]$ was more than unity for most of the traits in both F_1 and F_2 generations except for days of flowering and plant height indicating the involvement of over dominance.

General combining ability effects

The choice of parents for hybridization influences the success in any crop improvement program. The selection of parents based on *per-se* performance is not always good indicator of superior combining parents (Allard, 1960). Hence, the combining ability analyses serve as an important tool for selection of parents with highest breeding value. The parents with high general combining ability effects may be used for improvement of individual trait *per-se*. The GCA effects (Table 3) revealed that the genotypes GS234, LC185, Jawahar-17 and JLS-9 exhibited significant and negative value for days to 50% flowering and plant height in both the generations except LC185 for plant height in F_1. The negative and significant GCA effects suggested that these genotypes could be of better choice for developing early flowering and short stature varieties of linseed which are considered as desirable trait. The parental genotypes EC1392, JLS-9 for branches/plant, JLS-9, Hira, Mukta, LC-185, Neela for capsules/plant, Jawahar-17, LC-185 for seeds/capsules, JLS-9, Hira, Mukta for capsule weight/plant, JLS-9, Neela, Hira for seed weight/plant JLS-9, Jawahar-17, Hira Mukta for test weight, and LC-185, Mukta, Neelum for oil content were found to be good general combiners. The similarity in the estimate of the GCA effects in F_1 and F_2 generations indicated that the best combiners are stable in their performance over years and generations. Among different parental genotypes the JLS-9 showed GCA effect in desirable direction for maximum number of traits followed by LC-185, Hira, Mukta and Jawahar-17. Based on GCA effects the parental genotypes JLS-9, LC-185, Hira, Mukta and Jawahar-17 could be utilized in multiple crossing program involving all possible combinations followed by bi-parental mating to exploit the maximum variability towards development of high yielding early maturing linseed varieties. It was reported earlier by Kumar et al. (1994), Nie et al. (1991), Yang and Bo (1988) and Singh et al. (1987) that cultivars with high individual GCA effects can be utilized in breeding programs for producing a relatively higher percentage of superior yielding progeny. Srivastava et al. (2007) also reported that good general combiner plays an important role in developing population through crossing among them in all possible combinations. Abdel Moneam (2014) and Kumar et al. (2013) also recommended utilizing the parents with high GCA effects for developing desirable hybrids. High GCA effects are mostly due to additive gene effects or additive x additive interaction effects (Griffing, 1956). Diallel selective mating system (Jensen, 1970) and recurrent selection schemes will be most effective breeding procedures which help in accumulating desirable alleles within the base populations. Joshi et al. (2004) supported the role of diallel selective mating for multiple crossing which produces an elite population for selection of high yielding lines in advanced generations.

Specific combining ability effects

The estimates of specific combining ability (SCA) effects for all the trait presented in Table 4. In general, the SCA effects do not contribute tangibly in the improvement of self-fertilizing crops, except where commercial exploitation of heterosis is feasible. The SCA value represents the dominance and epistatic interactions which are non-fixable in

Table 1. Details of 10 linseed parental genotypes used in the present study.

Parental genotypes	Pedigree	Diagnostic feature
Neelum	T-1 x NP(RR)-9	Erect type, medium height, late flowering, high seed and oil yield, blue flower, brown seed color
Garima	T-29 x Neelum	Erect type, medium height, moderate flowering, high seed and oil yield, blue flower, light brown seed color
Jawahar-17	Selection of No. 55	Semi Erect type, short height, moderate flowering, low seed and oil yield, red violet flower, dark brown seed color
Neela	Selection	Semi Erect type, medium height, moderate flowering, average seed and oil yield, blue flower, brown seed color
EC1392	-	Erect type, medium height, moderate flowering, low seed and oil yield, white flower, light brown seed color
LC185	NP(RR)-37 x Kangra local	Erect type, medium height, moderate late flowering, low seed and high oil yield, blue flower, yellow seed color
JLS-9	(RL–102 x R-7) x J23	Erect type, short height, moderate flowering, average seed and oil yield, white flower, light brown seed color
Hira	H 342 x NP (RR) - 9	Erect type, tall height, moderate flowering, average seed and oil yield, white flower, dark brown seed color
Mukta	H 342 x NP (RR) - 9	Erect type, tall height, moderate flowering, average seed and high oil yield, white flower, brown seed color
GS 234	-	Erect type, short height, early flowering, average seed and oil yield, white flower, dark brown seed color

Table 2. Estimates of variance for combining ability for different quantitative traits in linseed.

Source	Generations	GCA	SCA	$\delta^2 g$	$\delta^2 s$	$\delta^2 g/ \delta^2 s$	$(\delta^2 s/ {}^2 g)^{0.5}$
df	-	9	45	-	-	-	-
Days of Flowering	F_1	738.6**	44.9**	61.48	44.10	1.39	0.85
	F_2	667.34**	47.97**	55.50	46.46	1.19	0.91
Plant height	F_1	544.09**	47.62**	44.83	41.59	1.08	0.96
	F_2	502.82**	49.06**	41.40	43.12	0.96	1.02
Branches/plant	F_1	1.91**	0.94**	0.14	0.77	0.18	2.35
	F_2	1.52**	0.68**	0.11	0.54	0.21	2.22
Capsule/plant	F_1	5171.78**	1999.46**	428.82	1973.52	0.21	2.15
	F_2	5963.20**	1979.22**	495.30	1959.42	0.25	1.99
Seed/capsule	F_1	1.59**	1.53**	0.12	1.47	0.08	3.50
	F_2	2.06**	1.35**	0.16	1.26	0.13	2.81
Capsule weight	F_1	19.26**	17.10**	1.58	16.88	0.09	3.27
	F_2	25.85**	18.27**	2.13	17.99	0.11	2.91
Seed weight	F_1	11.61**	11.78**	0.95	11.56	0.08	3.49
	F_2	22.16**	13.26**	1.82	13.04	0.14	2.68
Husk weight	F_1	1.29**	1.02**	0.09	0.82	0.11	3.02
	F_2	0.66*	1.11**	0.03	0.85	0.03	5.32
Test weight	F_1	3.71**	1.06**	0.30	1.00	0.30	1.83
	F_2	3.82**	1.03**	0.30	0.90	0.33	1.73
Oil content	F_1	11.32**	7.01**	0.92	6.77	0.13	2.71
	F_2	8.31**	11.20**	0.66	10.90	0.06	4.06

df = degree of freedom; *, ** significance at 5% &1%, respectively. $\delta^2 g$=general combining ability variance. $\delta^2 s$= specific combining ability variance. $(\delta^2 s/ {}^2 g)^{0.5}$= degree of dominance.

nature and related to heterosis (Griffing, 1956). Therefore, if both or one of the parents involved in the crosses with high SCA values they could be successfully exploited in varietal improvement program and expected to give superior transgressive segregants (Kumar et al., 1994, Nie et al., 1991, Mishra and Rai, 1996). In the present investigation, substantial number of crosses exhibited significant specific combining ability (SCA) effects but none of the crosses were consistent for all the traits in both the generations. Out of 45 crosses 12 crosses i.e., Neelam x Mukta, Neelam x GS234, Garima x LC 185, JWR-17 x LC 185, JWR -17 x GS 234, Neela x EC-1392, Neela x JLS-9, Neela x Hira, EC-1392 x Mukta and Hira x Mukta showed significant and negative SCA effects for days to 50% flowering in both F_1 and F_2 indicating that these crosses were the best for earliness character. These divergent crosses producing best hybrid combinations with negative SCA effects may be due to contribution of favorable alleles from their parents. For plant height, significant negative SCA effects were observed in the crosses Neelam x Neela, Garima x Mukta, Jawahar-17 x Neela, JLS-9 x Hira, JLS-9x Mukta and JLS-9 x GS234 in both the generations denoting them as best hybrid combination for short stature plants. For branches/plant, crosses Neelam x Neela, Neelam x LC 185, Jawahar-17 x LC-185, Jawahar-17 x GS234, Neela x Mukta, EC1392 x Hira, and Mukta x GS234 gave significant and positive SCA effects in both F_1 and F_2 indicating that these crosses were the best combinations for this trait. For capsules/plant the crosses

Table 3. Estimates of general combining ability (GCA) effects of 10 parental lines for 10 quantitative traits in Linseed.

Traits	Gene-ration	Parents										
		Neelam	Garima	Jawahar-17	Neela	EC1392	LC185	JLS-9	Hira	Mukta	GS 234	S.E.(gi)
Days of 50%	F1	0.33	0.18	-4.60**	2.35**	9.56**	-10.26**	-3.57**	7.63**	10.59**	-12.17**	0.25
Flowering	F2	-0.74*	-0.26	-4.45**	1.58**	9.77**	-9.44**	-4.56**	8.30**	9.97**	-10.17**	0.31
Plant height	F1	9.79**	-8.53**	-3.94**	3.41**	1.44*	1.06	-4.77**	4.80**	7.24**	-10.51**	0.67
	F2	9.60**	0.38	-0.19	2.01**	-0.60	-3.03**	-5.40**	5.02**	5.76**	-13.54**	0.66
Branches/plant	F1	-0.31**	-0.67**	-0.22	-0.01	0.66**	-0.23*	0.55**	-0.006	0.18	0.06	0.11
	F2	-0.46**	-0.21*	-0.68**	0.06	0.40**	0.02	0.34**	0.13	0.32**	0.08	0.10
Capsules/plant	F1	-28.15**	-28.47**	-5.56**	15.25**	-6.58**	15.94**	37.21**	4.02**	10.57**	-14.51**	1.39
	F2	-26.68**	-35.31**	-5.56**	11.38**	-4.32**	6.30**	44.94**	7.87**	10.97**	-9.58**	1.21
Seeds/capsule	F1	0.05	-0.17*	0.71**	-0.36**	-0.14*	0.29**	0.40**	-0.13**	-0.25**	0.83**	0.06
	F2	-0.31**	-0.53**	0.59**	0.26**	0.14	0.63**	-0.009	-0.04	-0.49**	-0.24**	0.08
Capsule weight/plant	F1	-0.62**	-2.32**	0.11	0.54	-0.53**	-0.34**	2.13**	1.25**	0.83**	-1.06**	0.12
	F2	-1.48**	-2.73**	-0.01	0.90**	-0.16	0.05	2.36**	1.35**	0.68**	-0.96**	0.14
Seed weight/plant	F1	-0.62**	-1.82**	0.24	0.55**	-1.51	-0.40**	1.70**	0.80**	-0.50**	0.80**	0.12
	F2	-1.19**	-2.67**	0.07	1.22*	-0.41**	0.04	1.89**	1.25**	0.67**	-0.87**	0.12
Husk weight/plant	F1	0.06	-0.50**	-0.12	-0.006	-0.37**	0.05	0.41**	0.45**	0.33**	-0.25*	0.12
	F2	-0.30*	-0.06	-0.08	-0.31*	0.25	0.01	0.46**	0.10	0.008	-0.08	0.14
Test weight	F1	0.23**	-0.33**	0.22**	-0.21**	-0.68**	-0.88**	0.83**	0.70**	0.23**	-0.11	0.06
	F2	0.32**	0.03	0.21*	-0.20*	-0.94**	-0.90**	0.78**	0.54**	0.19*	-0.05	0.09
Oil content	F1	0.71**	-0.40**	-0.25	-1.42**	-1.31**	1.80**	0.26	-0.16	0.79**	-0.01	0.13
	F2	0.32*	0.47**	-0.63**	1.63**	-0.01	1.05**	0.40**	-0.98**	0.38*	0.64**	0.14

SE= Standard Error; *, ** significance at 5% &1%, respectively.

Table 4. Estimates of specific combining ability (SCA) effects of 45 cross combinations involving 10 parental lines from 10x10 half diallel mating design for 10 quantitative traits in Linseed.

Sl. No	Crosses	Days to 50% flowering		Plant height		Branches/plant		Capsules/ plant		Seed/capsule		Capsule weight		Seed weight		Husk weight		Test weight		Oil content	
		F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
1	Neelam x Garima	-6.39**	1.55**	2.61**	-0.20	0.04	0.42**	-1.40	6.59**	-0.39**	-1.10**	-1.89**	-1.91**	-1.34**	-1.08**	-0.52**	-0.86**	1.12**	0.75**	0.78**	-0.79**
2	Neelam x Jawahar -17	2.83**	4.74**	-0.73	-6.96**	-0.27	0.12	14.11**	5.23**	1.28**	1.52**	2.16*	2.35**	2.66**	1.26**	-0.47**	1.11**	0.06	0.07	-2.80**	-2.34**
3	Neelam x Neela	-0.09	-3.76**	-3.13**	-5.83**	1.04**	0.66**	-23.70**	-26.81**	-0.37**	-0.90**	-3.59**	-3.63**	-2.54**	-3.57**	-1.05**	-0.09	-0.76**	-1.33**	-1.06**	-0.31
4	Neelam x EC1392	3.79**	-0.47	9.53**	2.54**	0.47*	-0.23	-1.72	-16.76**	0.44**	-0.15	2.11**	0.07	2.12**	0.76**	0.01	-0.69**	-0.33**	0.17	1.08**	-2.30**
5	Neelam x LC-185	0.96*	-2.26**	2.88**	0.01	0.71**	1.38**	-21.78**	-23.73**	0.30**	-0.05	0.56**	-0.94**	-0.59**	-0.66**	1.15**	-0.25**	-0.16	-0.10	1.13**	3.52**
6	Neelam x JLS-9	1.66**	5.75**	-3.04**	4.01**	0.68**	-0.03	48.70**	59.49**	0.36**	0.43**	5.01**	2.54**	2.63**	1.51**	2.39**	1.06**	-0.44**	-0.52**	1.11**	2.70**
7	Neelam x Hira	2.79**	-1.61**	5.58**	2.81**	0.04	-0.72**	9.46**	23.25**	-0.03	-0.30*	1.39**	1.12**	1.40**	1.09**	-0.01	-0.003	-0.72**	-1.28**	1.77**	-0.33
8	Neelam x Mukta	-2.30**	-4.88**	-0.49	-2.35**	-0.70**	-1.35**	9.67**	26.26**	0.42**	0.48**	2.44**	2.46**	1.96**	2.77**	0.44**	-0.31**	-0.54**	-1.46**	0.01	-2.17**
9	Neelam x GS234	-8.36**	-7.33**	3.73**	14.35**	-0.05	0.88**	39.84**	8.82**	1.11**	0.56**	1.97**	3.13**	2.18**	3.05**	-0.20	0.11	-2.46**	-1.44**	0.09	-0.73**
10	Garima x Jawahar -17	0.78*	3.13**	3.39**	-7.27**	1.38**	0.28	56.57**	53.90**	0.28**	0.41**	2.60**	5.07**	2.25**	2.95**	0.33	2.11**	0.16	-0.10	-4.01**	0.40
11	Garima x Neela	10.91**	14.62**	-3.70**	2.38**	-0.58**	-0.006	15.08**	2.82	0.22*	-0.61**	0.14	0.58**	0.84**	-0.19**	0.71**	0.81**	-0.35**	0.64**	-1.68**	-2.63**
12	Garima x EC1392	11.58**	8.57**	-7.50**	1.67	-0.06	-0.37**	1.92	-10.13**	-1.32**	0.79**	1.24**	1.62**	1.24**	1.48**	-0.01	0.11	0.74**	0.26	0.60**	1.21**
13	Garima x LC-185	-10.81**	-6.63**	-0.22	9.66**	0.63**	-0.99**	30.29**	-19.76**	1.13**	-1.15**	1.66**	-0.79**	1.56**	-0.64**	0.09	-0.15*	-0.75**	0.61**	-1.41**	-0.18
14	Garima x JLS-9	2.85**	-2.62**	-1.25**	5.70**	-1.05**	0.05	-60.97**	-54.93**	-0.03	-0.81**	-2.88**	-3.53**	-2.17**	-3.00**	-0.70**	-0.53**	-0.61**	-1.71**	-0.67**	-3.60**
15	Garima x Hira	0.41	-5.72**	-6.05**	-0.16	-0.59**	-0.46**	-32.12**	-24.10**	-0.37**	-0.51**	-2.40**	-4.05**	-1.20**	-2.62**	-1.17**	-1.43**	0.15	-0.23	2.18**	-0.01
16	Garima x Mukta	6.74**	8.63**	-5.84**	-6.59**	-0.91**	-0.25	-31.00**	-26.86**	1.38**	0.33**	-1.85**	-3.18**	-0.80**	-1.74**	-1.05**	-1.47**	-0.47**	-0.78**	2.65**	1.71**
17	Garima x GS234	3.21**	-2.91**	0.48	7.93**	0.13	0.98**	-18.27**	-11.50**	-1.09**	-0.17	-0.68**	-1.04**	-0.69**	0.03	0.001	-1.05**	-0.32**	0.47**	1.30**	3.78**
18	Jawahar-17x Neela	6.71**	-0.95*	-2.12**	-2.13**	-0.37*	0.89**	-25.62**	-36.36**	-0.99**	-0.68**	-1.79**	-4.74**	-2.65**	-4.34**	0.84**	-0.40**	0.18	0.26	-1.19**	-1.71**
19	Jawahar -17x EC1392	3.27**	12.96**	-6.85**	1.47	-0.27	-0.20	-55.17**	-33.88**	0.14	-1.30**	-2.48**	-3.33**	-2.64**	-2.97**	0.17	-0.34**	1.17**	0.44**	3.12**	5.53**
20	Jawahar -17x LC-185	-10.02**	-6.64**	4.75**	15.67**	1.38**	0.71**	10.82**	9.28**	0.61**	2.10**	1.32**	2.77**	0.46**	3.33**	0.85**	-0.57**	0.24**	-0.16	-5.53*	-7.30**
21	Jawahar -17x JLS-9	4.30**	-4.46**	-5.30**	4.04**	-0.07	-0.37**	-34.44**	-10.49**	-0.15	-0.11	-1.12**	1.79**	0.97**	2.04**	-0.14	-0.25**	-1.34**	0.01	2.11**	-1.25**
22	Jawahar -17x Hira	-0.92*	3.89**	7.02**	1.61	0.15	-0.30*	55.50**	24.47**	0.50**	-0.58**	6.15**	2.48**	5.33**	1.82**	0.81**	0.64**	1.22**	0.99**	2.73**	0.40
23	Jawahar -17x Mukta	-5.60**	-10.44**	1.57	0.21	0.96**	0.44**	33.29**	32.34**	-0.27**	-0.59**	2.44**	2.28**	2.99**	2.80**	-0.49**	-0.52**	0.06	-0.56**	0.34	-1.23**
24	Jawahar -17x GS234	-3.22**	-2.35**	1.33	3.61**	1.41**	0.65**	39.68**	36.94**	1.41**	0.42**	1.30**	-0.10	0.57**	-0.65**	0.72**	0.56**	1.41**	0.92**	4.22**	1.63**
25	Neela x EC-1392	-1.12**	-5.71**	3.24**	-1.63	1.17**	-0.42**	85.10**	82.30**	1.59**	0.86**	7.98**	5.40**	6.41**	4.38**	1.59**	1.01**	0.58**	0.43**	-2.13**	1.46**
26	Neela x LC-185	0.04	3.17**	8.52**	-0.32	-0.58**	1.18**	40.90**	14.87**	0.65**	1.24**	5.63**	4.99**	4.32**	5.42**	1.30**	-0.40**	1.26**	0.52**	0.27	-4.24**
27	Neela x JLS-9	-4.45**	-4.81**	3.23**	-3.29	0.94**	-0.13	17.39**	-34.40**	-0.21*	1.12**	-0.01	2.51**	-0.04	2.66**	0.03	-0.15*	-0.82**	-1.13**	4.25**	4.90**
28	Neela x Hira	-5.75**	-5.04**	7.89**	9.17**	-0.48**	0.51**	2.81	38.06**	0.74**	2.79**	1.73**	5.79**	0.62**	5.04**	1.09**	0.74**	0.39**	0.07	-1.65**	-2.79**
29	Neela x Mukta	2.67**	2.84**	2.97**	1.67	0.99**	0.78**	5.70**	35.76**	2.70**	1.80**	2.24**	2.49**	1.81**	2.79**	0.41*	-0.30*	0.34**	0.32**	3.28**	-1.00**
30	Neela x GS234	-0.61	6.03**	-4.12**	-0.65	0.64**	-0.63**	3.99	16.22**	-0.23*	-0.20	2.24**	1.10**	2.33**	0.50**	-0.09	0.55**	0.52**	0.37**	-3.36**	-1.16**
31	EC-1392 x LC185	-4.62**	1.55**	5.16**	-0.71	-0.16	1.08**	6.64**	-9.85**	0.90**	0.35**	-0.79**	-1.73**	-0.13	-1.43**	-0.69**	-0.30**	0.18	0.002	4.39**	3.97**
32	EC-1392 x JLS-9	-14.32**	-11.22**	8.53**	1.78	0.61**	0.30*	52.04**	68.04**	0.69**	0.80**	0.65**	3.01**	0.75**	2.27**	-0.09	0.77**	-1.60**	-1.65**	1.26**	-0.61**
33	EC-1392 x Hira	4.90**	-2.19**	0.76	-4.88**	2.63**	1.21**	28.56**	16.70**	0.73**	0.37**	1.60**	0.23	1.66**	0.58**	-0.06	-0.35**	-1.30**	-1.64**	-4.00**	-4.11**
34	EC-1392 x Mukta	-8.86**	-6.43**	1.41	8.71**	-0.88**	0.42**	48.11**	30.67**	-1.24**	-0.21	4.21**	7.63**	2.85**	4.93**	1.35**	2.70**	1.00**	0.66**	1.50**	3.20**
35	EC-1392 x GS234	-0.15	-0.61	14.60**	7.28**	-0.13	0.32*	-19.59**	11.14**	-0.55**	-0.15	-0.84**	0.74**	-1.42**	-1.32**	0.57**	2.05**	-0.54**	-1.11**	-5.25**	-5.98**
36	LC-185 x JLS-9	16.97**	13.75**	5.91**	-0.21	-0.72**	-0.28	-3.28	-11.02**	-0.10	-0.65**	-3.22**	-4.23**	-1.69**	-4.45	1.48**	0.21**	0.20*	-0.40**	-2.18**	-8.28**
37	LC-185 x Hira	12.87**	16.82**	2.10**	0.55	0.53**	1.09**	-12.90**	3.27	0.15	0.78**	-2.31**	1.41**	-1.82**	1.06**	-0.52**	0.34**	-0.50**	-0.49**	2.90**	5.07**
38	LC-185 x Mukta	5.16**	-1.64**	0.52	-10.71**	1.11**	-0.53**	27.21**	25.07**	-0.61**	0.16	3.86**	1.44**	3.70**	1.07**	0.16	0.37**	0.44**	0.25	-0.18	-0.76**
39	LC-185 x GS234	1.57**	-1.53**	-0.67	--9.17**	-0.79**	-0.72**	86.97**	121.5**	0.37**	0.81**	6.90**	10.79**	5.88**	8.68**	1.05**	2.09**	-0.42**	-0.22	1.86**	3.07**
40	JLS-9 x Hira	0.17	3.80**	-8.58**	-12.84**	0.27	0.26	43.42**	51.53**	1.95**	0.72**	4.13**	3.03**	4.03**	-0.40**	0.07	-0.40**	-1.34**	1..18**	-3.01**	1.15**
41	JLS-9 x Mukta	6.70**	9.23**	-6.30**	-10.37**	0.32	0.81**	50.17**	60.20**	2.74**	1.74**	5.65**	4.18**	5.39**	-0.04	0.26	-0.04	2.51**	1.93**	-3.17**	1.02**
42	JLS-9 x GS234	1.01**	2.71**	-3.17**	-9.17**	-0.35*	-1.04**	-36.39**	-37.56**	-1.16**	-1.96**	-1.74**	-2.40**	-1.75**	-0.58**	-0.01	-0.58**	0.40**	0.48**	2.63**	3.49**
43	Hira x Mukta	-6.16**	-3.20**	-11.60**	1.89	00.11	0.39**	18.83**	-4.86**	-0.72**	-1.29**	-1.20**	0.03	-1.73**	0.15*	0.55**	0.15*	-0.08	1.27**	-1.21**	-2.78**
44	Hira x GS234	-3.92**	1.51**	5.48**	-2.47**	-0.79**	-0.93**	1.46	-14.60**	-0.53**	-0.36**	1.93**	0.04	1.08**	0.04	0.84**	0.04	0.09	-1.20**	-0.06	-3.61**
45	Mukta x GS234	1.00**	4.17**	5.00**	-8.97**	0.48**	0.87**	-1.65	-33.36**	1.05**	0.91**	-0.18	-2.01**	-0.92**	0.07	0.73**	0.07	0.57**	0.77**	3.33**	3.54**
S.E. (sij)		0.75	0.95	2.04	2.01	0.34	0.30	4.20	3.67	0.20	0.25	0.38	0.43	0.38	0.12	0.37	0.14	0.19	0.28	0.40	0.45

*, ** significance at 5% &1%, respectively. S.E.=Standard Error.

Neelam x Jawahar-17, Neelam x JLS-9, Neelam x GS234, Garima x Jawahar-17, Jawahar-17 x GS234, Neela x EC1392, EC1392 x JLS-9, EC1392 X Mukta, LC-185 x GS234,and JLS-9 x Mukta showed highly significant and positive SCA effects in both the generations indicating that these cross combinations are superior for this particular trait. For capsule weight/plant, the cross combinations LC185 x GS234, JLS-9 x Mukta, EC-1392 x Mukta, Neela x LC-185, Jawahar-17 x Hira, Neela x LC185, Garima x Jawahar-17 and Neelam x Jawahar-17 have highly significant and positive SCA effects in both F_1 and F_2 indicating them as useful crosses for this character. For seed weight/plant the most prominent crosses were LC185 x GS234, Neela x EC-1392, Neela x LC185, EC-1392 x Mukta, Jawahar-17 x Hira, Garima x JWR-17, and Neelam x Jawahar-17. It was interesting to note that most of the prominent crosses were found to be common for both capsule weight/plant and seed weight/plant having positive and significant SCA values suggesting that these cross combinations could be successfully exploited for further yield improvement in linseed. Test weight considered as an important trait associated with crop yield and thus important crosses for test weight with significant and positive SCA effect values were JLS-9 X Mukta, Jawahar-17 x GS234, Jawahar-17 x Hira, Jawahar-17 x EC1392, and Neelam x Garima. For oil content the important crosses were Neela x JLS-9, Mukta x GS 234, JLS-9 x GS 234, LC185 x Hira, Jawahar-17 x GS234, Jawahar-17 x EC1392 and Garima x GS 234. It is evident that all the cross combinations, which expressed high SCA values for different traits involved high x high, high x low and low x low general combining ability parents showing the presence of additive and non-additive type of gene actions. But most of the crosses exhibiting high SCA effect have at least one parent with high GCA effect indicating that such combinations are expected to produce desirable transgressive segregants. Mohammadi et al. (2010) also observed significant SCA effects revealing meaningful contribution of additive and non-additive gene action for different traits in a diallel cross using eight flax genotypes. Abdel-Moneam (2014) reported that most of the superior crosses having significant SCA effect values for particular trait include at least one of their parents of high GCA effects for the same trait. Pali et al. (2014) evaluated fourteen parents in line x tester cross and revealed that additive and non-additive gene effects were important in controlling various studied characters.

Materials and Methods

Plant materials

The plant materials used in the present investigation includes 10 pure genotypes namely Neelam, Garima, Jawahar-17, Neela, EC1392, LC185, JLS-9, Heera, Mukta and GS234 selected from active germplasm stock of linseed maintained at CSIR-National Botanical Research Institute, Lucknow, India. The details of the genotypes are presented in Table 1. These genotypes were crossed in diallel design (excluding reciprocals) and produced seeds for 45 F_1 hybrids. All the F_1 hybrids were raised to get F_2 seeds and a fresh F_1s were also made. The final experiment was conducted with 45 each F_1s, F_2s alongwith 10 parental genotypes.

Experimental site

The experimental field was situated between $26^0$40´N latitude and $80^0$45´E longitude and an altitude of 129 m above sea level. The average rainfall during the crop period (November 2014– April 2015) ranged from 3.8 mm to 21.9 mm and average day night temperature varied between 22 - 38.0^0C and 4.1 - 20.5^0C, respectively.

Experimental design

The experiment was conducted in randomized block design with three replications during crop season 2014-15. Each plot of parental genotypes and F_1s had two rows while F_2s had four rows of 2 meter long with spacing of 15 cm within rows and 45 cm between rows. Non-experimental rows were also sown to check the border effect. All the recommended agricultural practices such as fertilizer dose, crop protection measures, irrigation etc. were followed to raise a healthy linseed crop. Five plants from parental genotypes and F_{1s} and 15 plants from F_2s were randomly tagged for observations on days to 50% flowering, plant height (cm), branches/plant, branches/plant, capsules/plant, seeds/capsule, capsule weight/plant (g), seed weight/plant (g), husk weight/plant (g), test weight (g) and oil content (%).

Statistical analysis

The mean values from each replication of individual character were calculated and used for statistical analysis. The data were first subjected to the analysis of variance (ANOVA) following randomized block design (Panse and Sukhatme, 1985). The combining ability analysis viz., general combining ability and specific combing ability was estimated as per according to the method of Griffing (1956).

Conclusion

Through the present investigation important parental genotypes such as JLS-9, LC-185, Hira, Mukta and Jawahar-17 have been identified that could be utilized in multiple crossing program involving all possible combinations to exploit the maximum variability towards the development of high yielding early maturing linseed varieties. Significant GCA and SCA effects for the studied traits implies that the both additive and non-additive components of gene actions were involved in the inheritance. The prevalence of additive gene action in various characters implies their potential for genetic improvement through accumulating favorable alleles from parents with high GCA in the target genotype using appropriate methods such as diallele selective mating or recurrent selection.

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