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COMBINING ABILITY, GENE ACTION AND HETEROSIS FOR SEED YIELD AND ITS ATTRIBUTES IN LINSEED (*Linum usitatissimum* L.)

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SUMMARY

A line x tester analysis using 4 lines and 3 testers was carried out to study the combining ability, heterosis and gene action for seed yield and related traits in linseed. Analysis of variance for combining ability revealed that significant difference among the mean squares was observed for lines, testers and lines x testers for all the characters except for mean squares due to tester for seeds per capsule which indicated that experimental material possessed considerable variability. The ratio of GCA and SCA variance indicated the predominance of non-additive gene action for all the characters under study. Among the lines, Chambal and HimAlsi-2 and the testers HimAlsi-1 and Nagarkot displayed high *gca* effect and considered as good general combiners for most of characters. Significant positive SCA effect for seed yield per plant was displayed by the cross HimAlsi-2 x EC-541194, T-397 x HimAlsi-1, Chambal x Nagarkot, Kangra Local x EC-541194, HimAlsi-2 x HimAlsi-1 and T-397 x Nagarkot. These crosses have been identified as best hybrids for improving seed yield per plant. Heterosis was worked out over mid parent and better parent, for seed yield per plant crosses T-397 x Nagarkot, T-397 x HimAlsi-1, Chambal x Nagarkot, Chambal x HimAlsi-1, Chambal x EC-541194 Kangra Local x EC-541194, HimAlsi-2 x HimAlsi-1 and HimAlsi-2 x EC-541194 exhibited significant positive heterosis for both mid and better parent. Hence, these crosses would be exploited for isolating transgressive segregants for seed yield and its related traits for genetic improvement in linseed.

Key words: Linseed, combining ability, heterosis, gene action, line x tester

Key findings: This study identified some promising cross combinations based upon the combining ability and heterosis and these cross combinations could be exploited for genetic improvement in linseed.

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INTRODUCTION

Linseed (*Linum usitatissimum* L.) commonly known as *alsi*, is a multipurpose *rabi* oilseed crop, cultivated for oil and fibre, which belongs to the family Linaceae having 14 genera. *Linum* has over 200 species with *Linum angustifolium* Huds (n = 15) being its probable progenitor, native to Mediterranean region and Southwest Asia. *Linum usitatissimum* is the only economically significant species of the family with semi-dehiscent and non-dehiscent capsules type (Savita 2011). The crop is predominantly self-pollinated but out-crossing (less than 2%) occasionally results from insect activity (Dilman and Hoper, 1928). Two morphologically distinct cultivated species of linseed are recognized, namely flax and linseed. The flax type is commercially grown for the extraction of fibre, whereas the linseed is meant for the extraction of oil from seeds and cake, as a by-product.

Linseed contains about 36 to 48% oil content which is high in unsaturated fatty acids, especially linolenic acid (Khan *et al.*, 2010). It has drying and hardening properties which is emanated from its high linolenic acid content, thus is mostly used for industrial purposes such as manufacturing of paints, varnishes, soaps and printing inks (Wakjira, 2007). The fibre is known for its high strength and durability, therefore, used in the manufacturing of cloth, water resistant pipes, paper and strawboard. The by-product, oil cake is a valuable dairy feed containing 36% protein, of which 85% is digestible. So, every part of linseed is utilized commercially either directly or after processing with numerous medicinal uses.

Despite huge benefits of linseed, it is grown in 2.73 million ha of area in the world with annual production and productivity of 2.52 million tonnes and 923 kg/ha, respectively. While, national production being 0.15 million tonnes from 0.32 million ha area with productivity of 473 kg/ha (Anonymous 2013). The major causes behind low production of linseed are due to cultivation mainly in marginal land coupled with biotic and abiotic stresses, poor crop management and unavailability of suitable hybrids.

The success of any hybrid breeding programme depends upon the choice of parents and clear knowledge of gene action for specific characters (Venkatesh *et al.*, 2001). Combining ability is one of the most effective tools in deciding the appropriate parents for hybridization especially when a large number of parental lines are available and most promising ones are to be identified on the basis of their ability to give superior hybrids Adelardo *et al.* (2006). Combining ability is a powerful tool to select good combiners and thus selecting the appropriate parental lines for hybridization programme. In addition, the information on nature of gene action will be helpful to develop efficient crop improvement programme. General combining ability is due to additive and additive × additive gene action and is fixable in nature while specific combining ability is due to non-additive gene action which may be due to dominance or epistasis or both and is non-fixable. The presence of non-additive genetic variance is the primary justification for initiating the hybrid breeding programme (Cockerham, 1961). Heterosis breeding is an important crop improvement method adopted in many crops all over the world. It is a quick and convenient way of combining desirable characters which has assumed greater significance in the production of F_1 hybrids (Ramesh *et al.*, 2013; Jhajharia *et al.*, 2013). Several workers like Singh *et al.* (1987); Thakur *et al.* (1987); Khorgade *et al.* (1990); Khorgade *et al.* (1993) have reported combining ability on seed yield and its attributing characters in linseed. Commercial exploitation of heterosis in linseed is regarded as a breakthrough in the field of linseed improvement for developing hybrids. Development of better hybrids using stable high yielding lines shall raise the yield of this crop. In order to achieve high yielding cross combination, it is essential to evaluate available promising diverse lines and their hybrid combinations for yield and yield components (Singh *et al.*, 2006). The aim of heterosis analysis is to find out the best combination of crosses giving high degree of heterobeltiosis and characterization of hybrids for commercial exploitation. The studies of heterosis in linseed have also been reported by Saraswat *et al.* (1993); Foster *et al.* (1998); Ratnaparkhi *et al.* (2005); Sharma *et al.* (2005); Reddy *et al.* (2013). There are several techniques for the evaluation of varieties or strains in terms of their combining ability especially line × tester analysis is one of them. This technique was developed by Kempthorne (1957).

This investigation was therefore undertaken to generate information on the nature and magnitude of gene action, heterosis and combining ability effects for yield and its component traits in linseed.

MATERIALS AND METHODS

Plant material and crossing design

The present investigation was carried out at the experimental farm of Department of Crop Improvement, CSK, Himachal Pradesh Krishi Vishvavidyalaya, Palampur, Himachal Pradesh India, situated (32°8´N, 76°3´E) represents humid sub-temperate climate zone with annual rainfall of 2500mm and acidic soil with pH of 5.0 to 5.6, involving 19 diverse genotypes (4 lines, 3 testers) of *Linum usitatissimum* L. (Table 1). Twelve crosses in line × tester fashion were made during *rabi* 2012-13. Seeds of all crosses and their parents were sown in the field following RBD with 3 replications during *rabi* 2013-14 with the distance of 10 cm and 30 cm for plant to plant and row to row, respectively.

Table 1. List of linseed accessions/lines and their parentage/source used in the study.

No.	Lines/Testers	Parentage/Source
Lines		
1	T-397	T-491 x T-1193-2
2	Chambal	Local × RR 45
3	Kangra Local	Local variety
4	HimAlsi-2	EC-21741 x LC-216
Testers		
1	Nagarkot	New River x LC-216
2	HimAlsi-1	K-2 x TLP-1
3	EC-541194	Wild Species

Data recording and statistical analysis

Data were recorded on 5 randomly selected plants in each replication for plant height data was recorded by measuring the distance from the soil to the tip of the plant, at a stage when crop reached physiological maturity, technical height recorded from the ground surface to the point from where the primary branches start at the stage of physiological maturity, primary branches per plant is the numbers of branches emerging from the main stem were counted for each plant at maturity and then averaged, secondary branches per plant was counted of branches arising from primary branches in selected plants of each genotype were recorded and mean value was obtained, capsules per plant were counted total numbers of capsules in the plant and mean value was obtained, biological yield was recorded by weighing 5 selected plants before threshing and then averaged, seeds per capsule were counted in 10 randomly selected capsules and then averaged, straw yield per plant was recorded by weighing 5 selected plant after threshing and then averaged, seed yield per plant was recorded by weighing seed of 5 selected plant and averaged, seed yield per plod was recorded on the plot basis, while 1000- seed per entry per replication were also weighed and Harvest index was calculated as:

$$\text{Harvest index (\%)} = \frac{\text{Seed yield per plant}}{\text{Aerial biomass per plant}} \times 100$$

The collected data on above characters were subjected to analysis of variance (Singh and Chaudhary, 1977), heterosis, general and specific combining abilities analysis were carried out as per the standard procedure of line x tester described by Kempthorne (1957), using the OPSTAT software.

RESULTS AND DISCUSSION

The knowledge of genetic nature of quantitative characters is a basic requirement for purposeful management of genetic variability. In this study, 7 parents were chosen and data from Line x Tester were analyzed in the F_1 generation for 12 inherited characters, to assess the general nature of the genetic control of important characters in Linseed.

The analysis of variance revealed significant differences among the parents (lines and testers), lines *vs* testers, parents *vs* crosses and crosses for all the characters studied except for 1000 seed weight in lines *vs* testers and harvest index for tester and lines *vs* testers (Table 2) Similar results were also reported by Singh *et al.* (1987); Thakur *et al.* (1987); Khorgade *et al.* (1990).

Likewise the analysis of variance for combining ability exhibited significant differences among line x testers for all the characters studied thereby suggesting that the experimental material possessed considerable variability (Table 3). The lines expressed significant differences for all the characters under study while the testers exhibited significant differences for all the characters except seeds per capsule.

Estimates of genetic component of variance for different characters presented in Table 3 revealed that the variances due to lines (σ^2l) were higher than the variances due to testers (σ^2t) for all the characters except capsules per plant, 1000 seed weight and harvest index indicating the role of lines towards total additive genetic variance (σ^2g). Estimates of σ^2g and σ^2s revealed that the magnitude of SCA variance were higher than those due to GCA variance for all the characters viz., plant height, technical height, primary branches, secondary branches, capsules per plant, biological yield per plant, seeds per capsule, straw yield per plant, seed yield per plant, seed yield per plot, 1000 seed weight and harvest index, indicating greater role of non-additive gene action in the control of these characters as reported earlier by Kumar *et al.* (2000); Bhateria *et al. (*2001). This was also confirmed by ratio of σ^2g: σ^2s which is less than unity for all characters. This emphasizes the fact that in linseed in the case of all these characters, to non-additive effects of genes involved in their control are much more important as compared additive effects although these too have a significant role. The preponderance of non-additive gene action for plant height, primary branches/plant, secondary branches/plant, capsules/plant, seeds/capsule, 1000- seed weight, seed yield/plant and harvest index is in accordance with the earlier studies of Thakur and Bhateria (1991); Tak (1996) Patel *et al.* (1997); Mahto and Rahman (1998); Kumar *et al.* (2000); Bhateria *et al.* (2001).

The average degree of dominance (σ^2s/ σ^2g)$^{1/2}$ was found greater than unity for all the characters also indicating the preponderance of non-additive gene action in the expression of all the characters studied and suggest the feasibility of exploitation of non-additive genetic variation for characters through hybrid breeding

The estimate of GCA effects of 7 parents (4 lines and 3 testers) for all the 12 attributes have been presented in Table 4. Based on the combining ability effects, the parents values were categorized in 3 groups as good, average and poor general combiners. The parents with significant GCA effects towards desirable direction were considered as good general combiners, with positive GCA effects were considered as average general combiners and the parents with negative GCA effects were designated as poor general combiners. An overall appraisal of GCA effects (Table 4) indicated that none of the parents was good general combiner simultaneously for all the characters studied. However, among the lines, Chambal was found to be good general combiner for 8 characters *viz.*, plant height, technical height, biological yield per plant, straw yield per plant, seed yield per plant, seed yield per plot, 1000 seed weight and harvest index followed by HimAlsi-2 for 7 characters *viz.*, plant height, technical height, capsules per plant, biological yield per plant, straw yield per plant, seed yield per plant and seed yield per plot. T-397 for 4 characters *viz.*, primary branches, secondary branches, seeds per capsule and 1000 seed weight and Kangra Local for 2 characters *viz.*, capsules per plant and seeds per capsule. Among the testers, HimAlsi-1 was good general combiner for 8 characters *viz.*, plant height, technical height, primary branches, secondary branches, biological yield per plant, seed yield per plant, seed yield per plot and 1000 seed weight followed by Nagarkot for 6 characters *viz.*, plant height, technical height, biological yield per plant, straw yield per plant, seed yield per plant, and seed yield per plot and EC-541194 for 2 characters *viz.*, capsules per plant and harvest index. Hence the parents *viz.*, Chambal, HimAlsi-1 HimAlsi-2 and Nagarkot which are good general combiners for most of characters

Table 2. Analysis of variance for lines, testers and their crosses for different characters in linseed.

Source	df	PH (cm)	TH (cm)	PB	SB	CP	BYP (g)	SC	StYP (g)	SYP (g)	SYPo (g)	SW (g)	HI (%)
Replication	2	4.99	3.82	1.14	0.84	8.32	1.60	1.32	0.34	0.26	12.44	0.76	0.38
Genotypes	18	329.63**	137.04**	21.74**	13.71**	192.62**	21.36**	1.65**	4.66**	3.93**	3368.96**	7.07**	66.17**
Crosses	11	235.90**	107.79**	17.63**	11.95**	156.07**	20.62**	1.73**	3.87**	3.92**	2586.14**	5.68**	65.53**
Parent	6	537.98**	212.11**	23.75**	12.42**	291.51**	16.40**	1.72**	4.89**	1.11**	4800.86**	10.42**	34.83**
Lines	3	433.76**	223.22**	28.35**	17.58**	31.59**	17.60**	2.67**	5.14**	0.62**	4114.97**	10.55**	67.00**
Testers	2	900.51**	300.86**	27.50**	7.54**	590.97**	22.77**	0.54**	6.78**	2.33**	8090.78**	15.43**	2.27
Lines v Testers	1	125.56**	1.28**	2.46**	6.70**	472.32**	0.04	1.20**	0.38**	0.16**	278.67**	0.01	3.43
Crosses vs Parents	1	110.55**	8.37**	54.88**	40.82**	1.37**	59.24**	0.29**	11.92**	20.96**	388.63**	2.25**	261.16**
Error	36	0.32	0.32	0.10	0.06	1.37	0.10	0.08	0.05	0.02	2.40	0.04	1.63

*, ** Significant at 5% and 1% levels, respectively; PH-plant height; TH- technical height; PB- primary branch; SB- secondary branch; CP-capsules per plant; BYP- biological yield per plant; SC-seeds per capsule; StYP- straw yield per plant; SYP-seed yield per plant; SYPo-seed yield per plot; SW-1000 seed weight and HI-harvest index.

Table 3. Analysis of variance for combining ability for lines, testers and their crosses.

Source	df	PH (cm)	TH (cm)	PB	SB	CP	BYP (g)	SC	StYP (g)	SYP (g)	SYPo (g)	SW (g)	HI (%)
Replication	2	4.77	4.32	1.28	1.15	6.52	1.56	1.00	0.45	0.15	17.86	0.60	1.16
Lines	3	614.99**	198.16**	26.66**	18.95**	189.76**	47.05**	4.72**	6.74**	8.53**	1476.52**	10.41**	18.33**
Testers	2	164.55**	252.00**	30.00**	18.06**	332.35**	15.85**	0.17	7.71**	1.06**	9170.11**	10.09**	31.38**
Lines x Testers	6	70.13**	14.54**	8.99**	6.41**	80.46**	8.99**	0.75**	1.15**	2.57**	946.30**	1.84**	100.52**
Error	22	0.30	0.25	0.10	0.03	0.17	0.06	0.09	0.04	0.01	0.98	0.05	0.93
Variance components													
$\sigma^2 l$		71.1	50.14	41.24	43.26	33.16	62.23	74.43	47.51	59.36	15.57	50.02	7.63
$\sigma^2 t$		12.68	42.51	30.94	27.48	38.72	13.97	1.83	36.25	4.9	64.47	32.32	8.71
$\sigma^2 lt$		16.22	7.36	27.82	29.26	28.12	23.79	23.74	16.23	35.74	19.96	17.67	83.67
$\sigma^2 g$		7.15	4.02	0.37	0.24	3.26	0.50	0.04	0.12	0.06	70.74	0.17	1.51
$\sigma^2 s$		23.28	4.76	2.97	2.13	26.76	2.98	0.22	0.37	0.85	315.10	0.59	33.20
$\sigma^2 g / \sigma^2 s$		0.31	0.84	0.13	0.11	0.12	0.17	0.19	0.32	0.07	0.22	0.28	0.05
$(\sigma^2 s / \sigma^2 g)^{1/2}$		1.80	1.09	2.82	2.98	2.86	2.44	2.29	1.78	3.83	2.11	1.90	4.69

*, ** Significant at 5% and 1% levels, respectively; PH-plant height; TH- technical height; PB- primary branch; SB- secondary branch; CP-capsules per plant; BYP- biological yield per plant; SC-seeds per capsule; StYP- straw yield per plant; SYP-seed yield per plant; SYPo-seed yield per plot; SW-1000 seed weight and HI-harvest index.

Table 4. Estimates for general combining ability (GCA) effects of parents for agro-morphological characters.

Characters	PH (cm)	TH (cm)	PB	SB	CP	BYP (g)	SC	StYP (g)	SYP (g)	SYPo (g)	SW (g)	HI (%)
Lines												
T-397	-10.70 **	-6.22 **	2.57 **	2.15 **	-5.49 **	-0.51 **	0.28 **	0.12 ns	-0.25 **	-5.67 **	0.68 **	-0.99 **
Chambal	5.77 **	2.09 **	-0.98 **	-0.43 **	-2.09 **	1.41 **	-0.97 **	0.24 **	0.82 **	15.78 **	0.73 **	2.07 **
Kangra Local	-2.28 **	-0.63 **	-1.00 **	-0.77 **	3.99 **	-3.00 **	0.74 **	-1.21 **	-1.27 **	-14.00 **	-1.57 **	-0.17
HimAlsi-2	7.21 **	4.76 **	-0.59 **	-0.95 **	3.59 **	2.10 **	-0.05	0.85 **	0.70 **	3.89 **	0.15	-0.91 *
SE (gi) ±	0.18	0.17	0.10	0.06	0.14	0.08	0.10	0.06	0.03	0.33	0.08	0.32
SE (gi-gj) ±	0.26	0.23	0.15	0.08	0.19	0.12	0.14	0.09	0.05	0.47	0.11	0.46
Testers												
Nagarkot	3.32 **	1.64 **	-1.45 **	-1.02 **	-4.13 **	0.86 **	-0.08	0.80 **	0.22 **	11.61 **	0.04	-1.04 **
HimAlsi -1	0.67 **	3.54 **	1.68 **	1.36 **	-1.79 **	0.45 **	0.14	-0.00	0.12 **	19.94 **	0.90 **	-0.83 **
EC-541194	-3.99 **	-5.18 **	-0.23 *	-0.34 **	5.92 **	-1.31 **	-0.06	-0.80 **	-0.34 **	-31.56 **	-0.94 **	1.86 **
SE (gi) ±	0.16	0.14	0.09	0.05	0.12	0.07	0.09	0.06	0.03	0.29	0.07	0.28
SE (gi-gj) ±	0.22	0.20	0.13	0.07	0.17	0.10	0.12	0.08	0.04	0.41	0.10	0.39

*, ** Significant at 5% and 1% levels, respectively; PH-plant height; TH- technical height; PB- primary branch; SB- secondary branch; CP-capsules per plant; BYP- biological yield per plant; SC-seeds per capsule; StYP- straw yield per plant; SYP-seed yield per plant; SYPo-seed yield per plot; SW-1000 seed weight and HI-harvest index.

Table 5. Estimates for specific combining ability (SCA) effects of parents for agro-morphological characters.

Characters	PH (cm)	TH (cm)	PB	SB	CP	BYP (g)	SC	StYP (g)	SYP (g)	SYPo (g)	SW (g)	HI (%)
Crosses												
T-397 x Nagarkot	-2.69 **	-1.84 **	-1.97 **	-1.54 **	4.82 **	2.19 **	-0.37 *	0.86 **	1.04 **	10.17 **	0.14	2.28 **
T-397 x Himalsi-1	1.26 **	1.24 **	-0.45 *	-0.25 *	2.84 **	-0.23	0.15	-0.39 **	0.12 *	16.83 **	-0.17	2.74 **
T-397 x x EC-541194	1.43 **	0.59	2.42 **	1.79 **	-7.66 **	-1.96 **	0.22	-0.47 **	-1.17 **	-27.00 **	0.03	-5.02 **
Chambal x Nagarkot	0.55	2.54 **	0.10	-0.05	0.42	-0.22	0.69 **	-0.08	0.35 **	-9.28 **	0.36 *	3.39 **
Chambal x HimAlsi-1	-4.83 **	-1.41 **	0.72 **	0.85 **	0.85 **	-0.96 **	0.04	-0.29 *	-0.42 **	-11.61 **	-1.16 **	0.10
Chambal x EC-541194	4.28 **	-1.13 **	-0.82 **	-0.80 **	-1.27 **	1.18 **	-0.73 **	0.37 **	0.08	20.89 **	0.80 **	-3.50 **
Kangra Local x Nagarkot	3.82 **	1.04 **	0.32	0.26 *	-1.12 **	0.87 **	0.01	-0.12	-0.20 **	4.83 **	-0.40 **	0.03
Kangra Local x HimAlsi 1	3.57 **	0.79 *	0.98 **	0.84 **	-2.00 **	1.53 **	-0.14	0.43 **	-0.01	-6.17 **	0.89 **	-6.67 **
Kangra Local x EC-541194	-7.39 **	-1.83 **	-1.30 **	-1.10 **	3.12 **	-0.66 **	0.13	-0.31 **	0.21 **	1.33 *	-0.48 **	6.64 **
HimAlsi -2 x Nagarkot	-1.67 **	-1.75 **	1.55 **	1.33 **	-4.11 **	-1.10 **	-0.33	-0.66 **	-1.19 **	-5.72 **	-0.09	-5.71 **
HimAlsi-2 x HimAlsi-1	-0.00	-0.62 *	-1.26 **	-1.44 **	-1.70 **	-0.35 *	-0.05	0.24 *	0.31 **	0.94	0.44 **	3.83 **
HimAlsi-2 x EC-541194	1.68 **	2.37 **	-0.29	0.11	5.81 **	1.44 **	0.38 *	0.41 **	0.88 **	4.78 **	-0.35 *	1.88 **
SE (gi) ±	0.31	0.29	0.18	0.10	0.24	0.14	0.17	0.11	0.06	0.57	0.13	0.56
SE (gi-gj) ±	0.45	0.41	0.25	0.14	0.34	0.20	0.24	0.16	0.08	0.81	0.19	0.79

*, ** Significant at 5% and 1% levels, respectively; PH-plant height; TH- technical height; PB- primary branch; SB- secondary branch; CP-capsules per plant; BYP- biological yield per plant; SC-seeds per capsule; StYP- straw yield per plant; SYP-seed yield per plant; SYPo-seed yield per plot; SW-1000 seed weight and HI-harvest index.

are considered as the potential parents and could be utilized in further breeding programme in order to exploit maximum genetic variability and combine more number of characters by involving fewer numbers of parents in a crossing programme.

SCA of a cross is the estimation and the understanding of the effect of non-additive gene action for a character. Non-additive gene action of a character is an indicator for the selection of a hybrid combination. Therefore, a highly significant SCA effect is desirable for a successful hybrid breeding programme. The estimation of SCA effects for 12 hybrids for all the twelve characters are presented in Table 5 significant positive or negative SCA effects were observed in F_1 generation for yield and various yields related traits. In the present investigation, none of the crosses expressed good specific combining ability effect for all the traits under study. Out of 12 crosses, 6 crosses showed significant and positive SCA effect for plant height, seed yield per plant, seed yield per plot and harvest index, 5 for technical height, secondary branches, capsules per plant, biological yield per plant and straw yield per plant, 4 for primary branches and 1000-seed weight and 2 for seeds per capsule. For seed yield per plant the cross combinations *viz.*, HimAlsi-2 x EC-541194, T-397 x HimAlsi-1, Chambal x Nagarkot, Kangra Local EC-541194, HimAlsi-2 x HimAlsi-1 and T-397 x Nagarkot which showed significant and positive SCA effects for seed yield per plant, also showed significant SCA effects for other important yield related characters. These individual crosses or their multiple cross combinations may be exploited developing broad genetic base population. The crosses where high SCA effects were observed involved all possible combinations between parents of high, low and average combining ability. This indicated that GCA, in general, had no bearing on the SCA effects of the crosses. High SCA effects manifested by crosses where both the parents were good general combiners might be attributed to additive × additive gene action. The high SCA effects of the crosses involving good × poor general combiner parents may be due the favourable additive effects of the good general combiner parent and epistatic effects of poor general combiner which supplemented the desirable plant attribute. High SCA effects expressed by low × low crosses might be ascribed to dominance × dominance type of non-allelic gene interaction producing over dominance thus being non-fixable. Under such situations, biparental mating or reciprocal recurrent selection followed by pedigree method of selection can be used for the improvement of seed yield in linseed (Singh, 2000). These finding corroborate with those of Kumar *et al.* (2000); Bhateria *et al.* (2001), who have reported that crosses showing desirable SCA effects involve good × good, good × poor and good × average general combiners. The crosses with high SCA effects involving low × low general combiner parents were highly sensitive to environments in heterozygous state due to non-additive effects.

The percentage of heterosis over mid parent and better parent for seed yield and its component characters is presented in Table 6. The estimates of heterosis showed that none of the hybrids were found to be significantly high heterosis (mid parent and better parent) for all the characters. Small and medium plant stature in linseed crop is preferred because it can tolerate heavy winds and can be prevented from lodging; therefore, negative heterosis is useful regarding plant height, present investigation revealed that heterosis ranged from -7.53 to 27.17% over mid parent and -22.67 to 8.89% over the better parent. However, technical height recorded -7.52 to 14.60% -27.31 to 5.33% heterosis over mid parent and better parent, receptively. In linseed, short stature with vigorous structure containing more number of branches provide opportunity for more yields, so positive heterosis is desirable for number of primary and secondary branches. Heterosis estimates over mid-parent showed that out of 12 crosses, 11 crosses showed positive significant heterosis while one cross showed negative heterosis, where values ranged from -5.47 to 55.61%. whereas, 9 crosses showed positive significant heterosis and 2 crosses showed negative heterosis over better parent for primary branches, while heterosis for secondary branches varied from -2.79 to 50.43 and -22.07 to 28.54% over mid parent and better parent, respectively.

Table 6. Estimates of heterosis (%) over mid parent (H1) and better parent (H2) for agro-morphological characters.

Characters	PH (cm)		TH (cm)		PB		SB		CP		BYP (g)	
	H_1	H_2	H_1	H_2	H_1	H_2	H_1	H_2	H_1	H_2	H_1	H_2
T-397 x Nagarkot	-7.53**	-22.67**	-7.52**	-27.31**	-5.47**	-25.58**	-2.79	-22.07**	-0.03	-2.46*	51.17**	16.24**
T-397 x HimAlsi-1	-0.25	-13.33**	4.92**	-19.25**	14.43**	6.98**	24.28**	8.66**	-2.01*	-6.80**	39.84**	18.12**
T-397 x EC-541194	17.22**	8.89**	6.19**	5.33*	55.61**	13.63**	50.43**	11.56**	-25.17**	-39.22**	16.86**	16.02**
Chambal x Nagarkot	4.51**	2.73**	4.94**	4.16**	12.65**	11.74**	11.31**	8.85**	-7.72**	-10.73**	14.44**	12.06**
Chambal x HimAlsi-1	-1.59**	-4.36**	-3.29**	-5.38**	25.93**	3.88	39.47**	28.54**	-4.76**	-5.43**	17.65**	6.71**
Chambal x EC-541194	27.17**	1.56*	-1.77	-22.74**	29.25**	17.28**	22.31**	7.96**	-13.12**	-26.05**	41.77**	10.09**
Kangra Local x Nagarkot	1.24*	-3.43**	4.31**	-5.25**	17.75**	14.17**	20.39**	13.43**	8.60**	4.78**	-15.91**	-31.17**
Kangra Local x HimAlsi 1	2.05**	1.84**	5.51**	-6.63**	30.69**	5.88**	45.53**	24.63**	8.64**	2.20*	21.21**	10.10**
Kangra Local x EC-541194	-2.04**	-19.89**	-0.57	-14.88**	25.58**	16.38**	23.63**	17.80**	9.33**	-11.97**	-10.58**	-18.08**
HimAlsi -2 x Nagarkot	0.39	-0.90	-1.78	-4.88**	28.05**	22.59**	19.82**	14.29**	-3.79**	-5.38**	15.35**	10.49**
HimAlsi-2 x HimAlsi-1	3.66**	-2.14**	2.82**	2.51*	5.90**	-8.82**	2.96	-2.80	3.02**	2.01*	33.72**	23.82**
HimAlsi-2 x EC-541194	20.51**	-5.88**	14.60**	-11.47**	33.55**	15.74**	24.57**	7.56**	8.54**	-8.89**	57.28**	24.16**
SE ±	0.40	0.46	0.40	0.46	0.23	0.26	0.18	0.20	0.39	0.45	0.22	0.25

(cont'd)

Characters	SC		StYP (g)		SYP (g)		SYPo (g)		SW (g)		HI (%)	
	H_1	H_2	H_1	H_2	H_1	H_2	H_1	H_2	H_1	H_2	H_1	H_2
T-397 x Nagarkot	-4.68	-13.51**	53.89**	19.02**	63.21**	34.24**	27.82**	2.52**	12.30**	11.51**	5.09*	-3.66
T-397 x HimAlsi-1	1.03	-5.02	46.64**	37.87**	48.17**	32.57**	31.59**	2.98**	8.31**	-2.30	4.64	-2.02
T-397 x EC-541194	-2.22	-6.56*	30.88**	30.43**	6.57	-0.92	4.37**	2.78*	23.46**	-3.57	-8.60**	-14.60**
Chambal x Nagarkot	0.00	-3.11	21.12**	5.69	55.34**	43.56**	1.73**	-0.01	5.03*	-3.69	35.77**	28.00**
Chambal x HimAlsi-1	-9.49**	-10.09**	30.74**	19.85**	45.95**	43.26**	1.28*	-0.31	-12.97**	-13.93**	22.96**	13.48**
Chambal x EC-541194	-23.64**	-25.42**	35.04**	16.73**	74.74**	44.46**	19.67**	-6.32**	22.67**	-10.31**	20.45**	11.38**
Kangra Local x Nagarkot	4.18	-6.74*	-4.81	-18.43**	-7.00*	-23.39**	5.56**	-4.36**	-8.99**	-30.55**	10.41**	9.54**
Kangra Local x HimAlsi 1	1.41	-5.99*	16.12**	8.58*	7.64*	-3.53	0.27	-11.77**	16.20**	-16.97**	-10.85**	-12.18**
Kangra Local x EC-541194	0.60	-5.24*	-16.69**	-26.65**	21.30**	12.57**	3.24**	-11.16**	-0.93	-3.45	35.66**	33.94**
HimAlsi -2 x Nagarkot	2.87	1.90	3.29	0.51	10.34**	1.69	2.42**	-0.67	1.53	0.01	-4.18	-7.98*
HimAlsi-2 x HimAlsi-1	5.75*	0.88	28.55**	2.05	65.39**	62.81**	6.43**	0.01	10.21**	-1.31	23.04**	15.61**
HimAlsi-2 x EC-541194	7.00*	0.42	21.95**	-7.69**	100.61**	66.23**	8.69**	-11.79**	6.96*	-15.96**	25.57**	18.24**
SE ±	0.20	0.23	0.16	0.18	0.09	0.10	1.10	1.27	0.14	0.17	0.90	1.04

*,** Significant at 5% and 1% levels, respectively; PH-plant height; TH- technical height; PB- primary branch; SB- secondary branch; CP-capsules per plant; BYP- biological yield per plant; SC-seeds per capsule; StYP- straw yield per plant; SYP-seed yield per plant; SYPo-seed yield per plot; SW-1000 seed weight and HI-harvest index.

Number of capsules per plant is known to directly associate with seed yield and for this trait, cross Kangra Local x EC-541194 (9.33), showed significantly high per cent mid parent heterosis, whereas cross Kangra Local x Nagarkot (4.78), showed significantly high % better parent heterosis. With respect to biological yield per plant, 10 crosses showed significant positive heterosis for both mid and better parent. Number of seeds per capsule is also an important yield component trait associated with higher seed yield in linseed, Crosses HimAlsi-2 x HimAlsi-1 and HimAlsi-2 x EC-541194 indicated significant positive heterosis over mid parent and none of the cross showed significant positive heterosis over better parent. For straw yield per plant out of 12 crosses, 9 and 6 crosses showed significant positive heterosis over mid parent and better parent respectively. The magnitude of heterosis for seed yield per plant varied from -7.00% (Kangra Local x Nagarkot) to 100.61% (HimAlsi-2 x EC-541194) and 23.39% (Kangra Local x Nagarkot) to 66.23% (HimAlsi-2 x EC-541194) over mid parent and better parent, respectively. Heterosis for yield was reflected through heterosis in yield components especially number of capsules plant confirming the earlier findings of many workers reported high degree of heterosis for seed yield in linseed *viz.*, Kansal and Gupta (1981); Dakhore *et al.* (1987); Rao *et al.* (1987); Saraswat *et al.* (1993); Foster *et al.* (1998); Kurt and Evans (1998); Reddy *et al.* (2013). For seed yield per plot, the magnitude of heterosis was maximum for T-397 x HimAlsi-1, 31.59 and 2.98% over mid parent and better parent, respectively. In linseed, 1000-seed weight serves as an indicator to the end product *i.e*., seed yield. The low seed yields in linseed hybrids are attributed mainly to the 1000-seed weight. For 1000- seed weight, eight hybrids showed significant positive heterosis over mid parent and one hybrid over better parent. Harvest index is also important character for linseed, for harvest index 8 crosses exhibited significant positive heterosis over mid parent, while 7 crosses showed significant positive heterosis over better parent.

However, the best general combiner parents and crosses with positive desirable direction, highest significant SCA and heterotic effects over mid and better parent for seed yield per plant presented in Table 7.

Table 7. List of heterotic crosses (%), good specific combinations and good general combiners for seed yield per plant.

Heterotic crosses over mid parent	Heterotic crosses over better parent	Good specific combination	Good general combiners
T-397 x Nagarkot	T-397 x Nagarkot	T-397 x Nagarkot	Chambal
T-397 x HimAlsi-1	T-397 x HimAlsi-1	T-397 x HimAlsi-1	HimAlsi-2
Chambal x Nagarkot	Chambal x Nagarkot	Chambal x Nagarkot	Nagarkot
Chambal x HimAlsi-1	Chambal x HimAlsi-1	Kangra Local EC-541194	HimAlsi -1
Chambal x EC-541194	Chambal x EC-541194	HimAlsi-2 x HimAlsi-1	
Kangra Local x HimAlsi 1	Kangra Local x EC-541194	HimAlsi-2 x EC-541194	
Kangra Local x EC-541194	HimAlsi-2 x HimAlsi-1		
HimAlsi -2 x Nagarkot	HimAlsi-2 x EC-541194		
HimAlsi-2 x HimAlsi-1			
HimAlsi-2 x EC-541194			

The results of the present investigation revealed that preponderance of non-additive type of gene actions was important in controlling various characters. The best combiners Chambal, HimAlsi-1 HimAlsi-2 and Nagarkot could be utilized in future breeding programmes while the crosses T-397 x Nagarkot, T-397 x HimAlsi-1, Chambal x Nagarkot, Chambal x HimAlsi-1, Chambal x EC-541194 Kangra Local x EC-541194, HimAlsi-2 x HimAlsi-1 and HimAlsi-2 x EC-541194 exhibited significant positive heterotic effect for yield and its important attributes Under such situations biparental mating or reciprocal recurrent selection followed by pedigree method of selection can be used for the improvement of seed yield in linseed.

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