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Combining Ability Analysis for Grain Yield and Its Component Traits in Linseed (*Linum usitatissimum* L.)

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Twenty-eight crosses generated from eight diverse parents of linseed (*Linum usitatissimum* L.) in diallel mating design (excluding reciprocal) were evaluated against Shekhar as check-in randomized block design for nine quantitative traits, to estimate the general combining ability (GCA) of the parents and specific combining ability (SCA) of crosses, for development of high yielding varieties. Analysis of variance revealed that the genotypes differed genetically from each other for all the nine characters studied. Combining ability analysis revealed that mean square due to GCA and SCA for days to 50 % flowering, days to 50 % maturity, plant height, number of primary branches, number seeds per capsules, oil percent and grain yield were significant. The genetic component of variances depicted that additive genetic variance was higher than non-additive genetic variance for plant height, number of capsules per plant and oil percent. Whereas, non-additive genetic variance was higher for the rest of the characters studied. SLS72 was found to be

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good general combiner for grain yield and its attributing traits viz. Oil percent, number of capsules per plant, shorter plant height and early flowering. Crosses PKDL71 x LCK7035, NL260 x SLS72, NL260 x Shekhar, RL26018 x Shekhar, LCK7035 x BAU-06-05 and RL26018 x LCK7035 showed higher positive significant SCA effects for grain yield per plant.

Keywords: Linseed; diallel; GCA; SCA and grain yield.

1. INTRODUCTION

Linseed (*Linum usitatissimum* L.) is an annual autogamous diploid (2x=2n=30) oilseed crop belonging to *Linaceae* family. It is the oldest domesticated and economically important industrial non-edible oilseed crop which is being cultivated for seed and its fibre since centuries. The whole plant has commercial use directly or indirectly and also has the capability to substantiate the existing natural demand for oil. 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 up to 65% of total fatty acid composition in linseed oil [1]. ALA has anti-inflammatory properties and has significant effects on inflammatory and autoimmune diseases including coronary heart disease, major depression, ageing, rheumatoid arthritis, Chrohn's disease and cancer [2]. Linseed oil also possesses superior drying qualities due to high linolenic acid content which renders it as an indispensable ingredient in paint and varnish, and 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 [3]. Linseed oil cakes to have very good nutritive feeding value for animals [4]. 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 that can be easily blended with cotton, hemp and jute to enhances its textiles properties [5]. Besides oil and fibre, lignin is another major compound obtained through linseed which acts as an antioxidant for humans. Flaxseed contains 800 times higher lignin’s than other plant seeds except for sesame [6]. Canada is the world’s largest producer of linseed accounting for almost 80% of the worldwide trade followed by China, the United States and India (FAOSTAT 2014). On the global scenario, India ranks second regarding area after Canada. Regarding production, it occupies fourth place after Canada, China and USA, respectively. It is one of the oldest crops grown for its seed and fibre and cultivated in over 2.6 million hectares with the production of 614,000 metric tons in the year 2013-14 (FAOSTAT, 2014). The crop is generally cultivated under marginal and rain-fed conditions. The average seed yield of linseed in India is 403 Kg/ha which is comparably very low in comparison with world average seed yield that is 943 Kg/ ha. The low seed yield is chiefly due to limited resources available to poor farmers along with non-availability of high-yielding cultivars. So, the development of high-yielding varieties/lines is needed to compete with other linseed growing countries. Such lines/varieties can easily be developed through suitable hybridisation and selection programmes to isolate superior segregants

The success of any hybridisation programme chiefly depends on combining the ability of parents used in crossing programme [7]. Selection of superior segregants followed by the selection of the best ones is the basic tasks of any breeding process [8]. This may be achieved on the basis of some objective criteria offered by the determination of the combining ability in parental forms used. To initiate an effective breeding programme, combining ability analysis is a powerful tool to identify parents with better potential to transmit desirable characteristics to the progenies and to identify the best specific crosses for yield parameters. Isolation of parental lines of good combining ability makes the pathway east, towards the success. The concept of combining ability plays a significant role in crop improvement, as it helps the breeder to study and compare the performance of the new lines in hybrids combination. It provides the base to select good combiners and also to understand the nature of gene action. Moreover, the exploitation of heterosis is primarily dependent on the development of high *per se* performing lines with good general combining ability. Griffing's [9] method of diallel analysis provides reliable information on the nature and magnitude of gene effects that contribute to the expression of various traits and helps plant breeder to select appropriate parents for hybridisation and producing desirable transgressive segregants.

Genetic improvement of quantitative traits is a continuous process, and information's 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 another set of experimental material with high accuracy [10]. 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. Keeping the above fact in mind, the present study was, therefore, undertaken with a view to estimating general and specific combining ability variances and effects to identify superior hybrids with good yield potential.

2. MATERIALS AND METHODS

The experimental material consisted of eight diverse genotypes viz., PKDL 71, LCK 7035, BAU-06-05, NDL- 2005-24, RL 26018, NL 260, SLS 72 and Shekhar of linseed were crossed in all possible combinations using diallel mating design (excluding reciprocals) to obtain 28 hybrids of linseed, during Rabi, 2011-12 at Agricultural Research Institute, Patna farm of Bihar Agricultural University, Sabour, Bhagalpur (Bihar). These twenty-eight hybrids, eight parents along with one standard check were evaluated in a randomised block design with three replications, in a single row plot of 4 m length with spacing of 25 cm row to row and 5 cm plant to plant, within a row in Rabi, 2012-13. All recommended agronomic practices were adopted to raise a healthy crop. The data were recorded from ten randomly selected competitive plants from each plot for plant height (cm), number of primary branches per plant, number of capsule per plant, number of seeds per capsule, 1000-seed weight and percentage of oil content in seed in each replication were recorded for statistical analysis. The character days to 50 per cent flowering and days to maturity were recorded on whole plot basis. The oil percentage in seed was analysed using NMR. The oil content calibration equation was determined using a modified Partial Least Square regression method (Wu et al., 2006). The mean value of the recorded data was subjected to analysis of variance using the statistical analysis procedures of Panse and Sukhatme, [11]. The combining ability analysis for the diallel mating design was performed according to Model-I and Method-II (parents and one set of F1's without reciprocals) proposed by Griffing [9].

3. RESULTS AND DISCUSSION

The analysis of variance for combining ability, using diallel mating design in respect of 28 crosses for all the nine characters is presented in Table 1. The analysis of variance revealed highly significant differences among the parents and their hybrids for all the nine quantitative traits indicating the existence of wider variability among the parental genotypes and the hybrids of linseed. The GCA and SCA variances were highly significant for all the traits studied except 1000-grain weight (Table 2). Highly significant mean sum of squares due to general and specific combining ability (GCA and SCA) for all the characters indicate that both additive and non-additive types of gene action were involved for the expression of these characters. Similar results were also reported by Mishra et al. [12] and Pali and Mehta [13]. Both general and specific combining ability were important but the former played an important role in the expression of all the characters. The magnitude of GCA variances was higher than that of SCA variances for all the traits which indicate the predominance of the additive gene effects for these characters. GCA/SCA variance was less than 1.0 for days to 50 percent flowering, days to maturity, number of primary branches, number of capsules per plant, 1000-grain weight and grain yield per plant indicates a preponderance of non-additive gene effects over additive genetic effects. This ratio was greater than 1.0 for the plant height, a number of seeds per capsules and the percent of oil content in the seeds, presenting the prevalence of additive gene action compared to non-additive gene action involving in the genetic control of these characters.

3.1 Estimates of Combining Ability Effects

The choice of parents for hybridisation influences the success in any crop improvement program. The selection of parents based on *per-se* performance is not always a good indicator of superior combining parents [14]. Hence, the combining ability analyses serve as an important tool for selection of parents with the highest breeding value. The parents with high general combining ability effects may be used for the improvement of individual trait *per-se*. The combining ability analysis was performed to obtain information on the selection of better

Table 1. Analysis of variance for diallel crosses for nine characters in linseed

Source of Variation	D.F.	Mean sum of squares								
		Days to 50% flowering	Days to 50% maturity	Plant height (cm)	Number of primary branch	Number of capsules per plant	Number of Seeds per capsules	1000-grain weight (g)	Oil percent	Grain yield per plant (g)
Replication	2	1.083	11.194	46.065	0.203	826.195	0.104	0.063	0.093	1.390
Treatments	35	24.495**	67.133**	178.853**	6.187**	2062.990**	7.124**	2.967**	11.562**	12.673**
Parents	7	47.518**	23.524**	277.565**	7.234**	1670.375**	2.684*	1.406	9.442**	3.238**
Hybrids	27	18.259**	79.907**	143.853**	5.997**	1865.740**	8.539**	2.395**	12.538**	10.060**
Parents Vs. Hybrids	1	31.720	27.524	432.858	4.014	10137.050	0.013	29.361	0.049	149.286
Error	70	1.188	5.080	5.960	0.294	50.499	0.070	0.060	0.041	0.258
Total	107	8.810	25.492	63.263	2.220	723.290	2.378	1.011	3.811	4.340

and = Significant at 0.05 and 0.01 levels, respectively*

Table 2. Analysis of variance and estimates of components of variance for combining ability for nine characters in linseed

Source of Variation	D.F.	Mean sum of squares								
		Days to 50% flowering	Days to 50% maturity	Plant height (cm)	Number of primary branch	Number of capsules per plant	Number of Seeds per capsules	1000-grain weight (g)	Oil percent	Grain yield per plant (g)
GCA	7	20.867**	23.117**	239.81**	3.52**	286.86**	4.25**	1.34	15.123**	4.703**
SCA	28	4.990**	22.193**	14.57**	1.70*	787.87**	1.91*	0.90	1.037*	4.105**
Error	70	0.396	1.693	1.99	0.10	16.83	0.02	0.02	0.014	0.086
Components of variance	**Mean sum of squares**									
	Days to 50% flowering		Days to 50% maturity	Plant height (cm)	Number of primary branch	Number of capsules per plant	Number of Seeds per capsules	1000-grain weight (g)	Oil percent	Grain yield per plant (g)
σ_g^2	1.5		0.092	22.52	0.181	50.1	0.23	0.04	1.40	0.05
σ_s^2	4.594		20.193	12.58	1.601	771.03	0.19	0.88	1.02	4.02
σ_g^2/σ_s^2	0.326		0.0045	1.80	0.11	0.06	1.22	0.04	1.37	0.01

and = Significant at 0.05 and 0.01 levels, respectively*

Table 3. General combining ability (GCA) effects of parental lines for nine characters in linseed

Sl. No.	Parents	Days to 50 % flowering	Days to maturity	Plant height (cm)	Number of primary branch	Number of capsules per plant	Number of Seeds per capsules	1000-grain weight (g)	Oil percent	Grain yield per plant (g)
1.	PKDL 71	0.833	0.150	-2.500**	0.821	-4.200**	0.304	-0.209	1.080	-0.358
2.	LCK 7035	-1.200	-0.350	0.533	0.181	0.033	-0.099	0.098	-0.004	0.072
3.	BAU-06-05	1.767	-0.450	9.000**	-0.583	-8.133**	0.407	-0.436	-1.031	-0.625
4.	NDL-2005-24	-0.033	-3.183**	-0.233	-0.052	1.467	-1.513	-0.502	-1.620	0.178
5.	RL26018	1.233	1.083	4.667**	-0.932	-4.300**	0.481	0.614	-0.716	0.118
6.	NL 260	-0.467	1.883	-1.000	-0.349	4.533**	0.428	0.134	-0.361	0.772
7.	SLS 72	-2.700**	-0.117	-4.067**	0.417	8.433**	-0.046	0.177	2.212*	2.758**
8.	Shekhar	0.567	0.983	-6.400**	0.497	2.167*	0.038	0.124	0.440	0.442
	SE (gi)	**0.186**	**0.385**	**0.417**	**0.093**	**1.214**	**0.045**	**0.042**	**0.035**	**0.087**
	SE(gi-gj)	**0.281**	**0.582**	**0.630**	**0.140**	**1.835**	**0.068**	**0.063**	**0.052**	**0.131**

and = Significant at 0.05 and 0.01 levels, respectively*

Table 4. Specific combining ability (SCA) effects of the hybrids for nine characters in linseed

Sl. No.	Hybrids	Days to 50% flowering	Days to maturity	Plant height (cm)	Number of primary branch	Number of capsules per plant	Number of seeds per capsules	1000-grain weight (g)	Oil percent	Grain yield per plant (g)
1.	PKDL71 x LCK7035	0.589	7.589**	3.596**	1.825*	47.833**	1.474	0.790	-0.264	4.166**
2.	PKDL71 x BAU-06-05	-0.044	1.022	5.463**	0.955	25.000**	0.034	0.390	-0.207	0.263
3.	PKDL71 x NDL2005-24	-0.244	-4.911**	0.030	0.025	-4.600**	-1.113	-0.476	-2.428**	0.583
4.	PKDL71 x RL26018	-2.511**	-5.178**	-1.537	-0.628	6.167**	-0.406	0.374	-0.485	-0.980
5.	PKDL71 x NL260	-0.478	4.022**	0.130	-0.945	14.333**	0.480	-0.213	1.633*	1.000
6.	PKDL71 x SLS72	0.756	2.022**	2.196**	0.022	14.433**	1.220	0.877	-0.107	1.280
7.	PKDL71 x Shekhar	-2.511**	-2.078**	0.196	-2.091**	-25.300**	1.237	0.797	0.928	0.430
8.	LCK7035 x BAU-06-05	1.322	4.856**	-2.570**	1.462	18.100**	0.570	0.150	0.834	2.100**
9.	LCK7035 x NDL2005-24	-5.544**	-2.744**	0.330	-0.501	-59.500**	-1.110	-1.683*	0.853	-1.780
10.	LCK7035 x RL26018	0.189	-5.678**	0.096	-0.688	3.267**	-0.603	0.467	-0.434	-1.177
11.	LCK7035 x NL260	-3.111**	-11.144**	1.096	-1.805*	-41.567**	-0.453	0.680	-0.059	-0.697
12.	LCK7035x SLS72	-2.211**	0.522	-3.504**	-1.071	-7.800**	0.624	0.337	0.414	-0.250
13.	LCK7035 x Shekhar	-0.478	2.422**	3.163**	0.582	15.800**	0.940	0.357	-0.491	1.300
14.	BAU-06-05 x NDL2005-24	0.156	-0.978	6.863**	-0.305	-25.335**	-1.616	-0.883	-1.570	-1.150
15.	BAU-06-05 x RL26018	-0.444	-1.578	1.296	-0.225	1.433	-0.543	0.734	-0.374	0.420
16.	BAU-06-05 x NL260	-2.078**	-4.711**	-1.037	-0.475	15.600**	0.410	0.180	-0.796	0.366
17.	BAU-06-05 x SLS72	0.822	1.956*	1.030	0.292	19.700**	0.784	0.804	1.058	1.546
18.	BAU-06-05 x Shekhar	-1.778*	0.856	4.363**	-0.155	6.967**	1.234	0.990	0.439	0.063
19.	NDL2005-24 x RL26018	1.356	0.156	-0.470	-0.055	25.500**	-1.290	0.660	-0.032	0.506
20.	NDL2005-24 x NL260	0.056	-0.311	0.196	0.095	15.667**	-1.303	1.180	-1.100	0.053
21.	NDL2005-24 x SLS72	0.289	3.022**	0.263	-0.805	11.100**	-0.330	0.804	0.413	0.533
22.	NDL2005-24 x Shekhar	-0.644	-4.411**	-6.737**	-0.118	23.033**	-1.713*	0.757	-0.802	-0.084
23.	RL26018 x LCK7035	0.789	7.422**	3.963**	1.675*	7.767**	0.537	0.397	0.186	1.923*
24.	RL26018 x SLS72	1.356	0.422	0.696	-0.625	-41.467**	-0.023	0.154	1.083	-0.664
25.	RL26018 x Shekhar	1.089	3.989**	0.696	-0.571	14.800**	1.227	0.040	0.041	2.420**
26.	NL260 x SLS72	4.389**	5.956**	1.363	2.992**	34.033**	1.230	0.400	0.478	2.616**
27.	NL260 x Shekhar	1.456	5.522**	4.363**	2.479**	26.300**	0.647	0.554	0.423	2.533**
28.	SLS72 x Shekhar	-0.644	-0.478	4.430**	1.545	3.733**	-2.313**	-1.756*	0.046	0.280
	SE (Sij)	**0.574**	**1.180**	**1.278**	**0.284**	**3.720**	**0.134**	**0.128**	**0.106**	**0.266**
	SE(sij-Sik)	**0.844**	**1.746**	**1.891**	**0.420**	**5.505**	**0.204**	**0.190**	**0.157**	**0.393**

and = Significant at 0.05 and 0.01 levels, respectively*

Table 5. Estimation of heterosis over better parent and check parent in twenty eight hybrids of linseed

Sl. No.	Hybrids	Days to 50% flowering		Days to maturity		Plant height (cm)		Number of primary branch per plant	
		Heterobeltiosis	Standard heterosis	Heterobeltiosis	Standard heterosis	Heterobeltiosis	Standard heterosis	Heterobeltiosis	Standard heterosis
1	PKDL71 x LCK7035	-5.551**	-3.485**	-4.190**	7.181**	-10.003**	33.722**	9.390**	42.381**
2	PKDL71 x BAU-06-05	-2.564**	-0.432	1.391	1.440	1.915*	51.432**	-10.610**	16.349**
3	PKDL71 x NDL2005-24	-5.128**	-3.053**	8.657**	-6.034**	-14.999**	26.299**	-15.488**	10.000**
4	PKDL71 x RL26018	-6.410**	-4.363**	5.305**	-2.586**	-11.157**	32.008**	-34.146**	-14.286**
5	PKDL71 x NL260	-5.987**	-3.930**	-3.076**	6.034**	-15.772**	25.150**	-30.854**	-10.000**
6	PKDL71 x SLS72	-7.269**	-5.240**	0.277	2.586**	-16.926**	23.436**	-9.756**	17.460**
7	PKDL71 x Shekhar	-7.269**	-5.240**	2.791**	0.000	-21.922**	16.012**	-34.512**	-14.762**
8	LCK7035 x BAU-06-05	-3.423**	-1.310	-1.399	4.310**	-3.854**	42.860**	-12.195**	14.286**
9	LCK7035 x NDL2005-24	-14.526**	-12.656**	-7.257**	-4.595**	-11.157**	32.008**	-29.634**	-8.413**
10	LCK7035 x RL26018	-5.551**	-3.485**	-6.143**	-3.448**	-5.769**	40.014**	-42.683**	-25.397**
11	LCK7035 x NL260	-11.962**	-10.035**	-10.056**	-7.474**	-11.157**	32.008**	-49.146**	-33.810**
12	LCK7035x SLS72	-13.679**	-11.791**	-1.953*	0.862	-20.007**	18.858**	-30.854**	-10.000**
13	LCK7035 x Shekhar	-7.269**	-5.240**	-0.561	3.448**	-15.011**	26.282**	-9.756**	17.460**
14	BAU-06-05 x NDL2005-24	-3.423**	-1.310	-5.866**	-3.164**	6.150**	57.723**	-36.585**	-17.460**
15	BAU-06-05 x RL26018	-2.564**	-0.432	-2.791**	0.000	5.377**	56.575**	-46.341**	-30.159**
16	BAU-06-05 x NL260	-6.846**	-4.808**	-4.743**	-2.009**	-3.854**	42.860**	-42.317**	-24.921**
17	BAU-06-05 x SLS72	-5.987**	-3.930**	-0.838	2.009**	-5.007**	41.145**	-23.537**	-0.476
18	BAU-06-05 x Shekhar	-5.128**	-3.053**	-0.838	2.009**	-3.854**	42.860**	-28.049**	-6.349**
19	NDL2005-24 x RL26018	-2.564**	-0.432	-3.629**	-0.862	-7.315**	37.716**	-37.805**	-19.048**
20	NDL2005-24 x NL260	-6.410**	-4.363**	-3.352**	-0.578	-13.084**	29.145**	-28.902**	-7.460**
21	NDL2005-24 x SLS72	-8.974**	-6.983**	-2.229**	0.578	-16.546**	24.001**	-30.488**	-9.524**
22	NDL2005-24 x Shekhar	-5.987**	-3.930**	-1.676*	1.147	-27.310**	8.006**	-21.098**	2.698**
23	RL26018 x NL260	-3.846**	-1.742*	-6.704**	9.767**	-3.081**	44.008**	-20.366**	3.651**
24	RL26018 x SLS72	-5.987**	-3.930**	-0.838	2.009**	-10.384**	33.156**	-39.024**	-20.635**
25	RL26018 x Shekhar	-2.141**	0.000	-3.076**	6.034**	-13.084**	29.145**	-37.439**	-18.571**
26	NL260 x SLS72	-4.282**	-2.188**	-4.475**	7.474**	-16.153**	24.584**	12.195**	46.032**
27	NL260x Shekhar	-3.846**	-1.742*	-5.028**	8.043**	-15.392**	25.716**	6.829**	39.048**
28	SLS72 x Shekhar	-9.410**	-7.428**	-1.676*	1.147	-18.853**	20.573**	4.878**	36.508**

and = Significant at 0.05 and 0.01 levels, respectively*

Table 5. Contd.

Sl. No.	Hybrids	No. of capsules/ plant		No. of seeds/capsule		1000-grain weight (g)		Oil percent		Grain yield/plant(g)	
		Heterobeltiosis	Standard heterosis	Heterobeltiosis	Standard heterosis	Heterobeltiosis	Standard heterosis	Heterobeltiosis	Standard heterosis	Heterobeltiosis	Standard heterosis
1	PKDL71 x LCK7035	24.488**	80.899**	1.889*	34.844**	10.122**	16.818**	-5.961**	0.121	71.617**	124.423**
2	PKDL71 x BAU-06-05	0.518	46.067**	-9.091**	20.313**	-1.220	4.787**	-8.203**	-2.267**	3.970**	35.962**
3	PKDL71 x NDL2005-24	-14.946**	23.596**	-45.336**	-27.656**	-12.561**	-7.245**	-16.179**	-10.759**	0.441	31.346**
4	PKDL71 x RL26018	-11.080**	29.213**	-13.459**	14.531**	11.341**	18.111**	-7.834**	-1.874*	-3.382**	26.346**
5	PKDL71 x NL260	2.064**	48.315**	-3.542**	27.656**	-1.585	4.398**	-1.079	5.319**	35.294**	76.923**
6	PKDL71 x SLS72	5.157**	52.809**	-0.472	31.719**	12.195**	19.017**	1.249	7.797**	39.264**	82.115**
7	PKDL71 x Shekhar	-30.411**	1.124	0.708	33.281**	10.610**	17.335**	-0.795	5.621**	22.058**	59.615**
8	LCK7035 x BAU-06-05	-1.546	43.067**	-7.556**	22.344**	-0.366	5.692**	-8.317**	-2.387**	37.205**	79.423**
9	LCK7035 x NDL2005-24	-54.125**	-33.337**	-50.059**	-33.906**	-23.537**	-18.887**	-9.935**	-4.110**	-27.941**	-5.769**
10	LCK7035 x RL26018	-10.052**	30.708**	-20.543**	5.156**	16.220**	23.286**	-11.042**	-5.289**	0	30.769**
11	LCK7035 x NL260	-37.888**	-9.742**	-19.362**	6.719**	13.049**	19.922**	-8.941**	-3.052**	16.617**	52.500**
12	LCK7035x SLS72	-8.761**	32.584**	-12.279**	16.094**	9.390**	16.041**	-0.312	6.135**	23.088**	60.962**
13	LCK7035 x Shekhar	4.639**	52.056**	-7.556**	22.344**	8.902**	15.524**	-7.919**	-1.964**	41.176**	84.615**
14	BAU-06-05 x NDL2005-24	-34.021**	-4.124**	-50.059**	-33.906**	-20.366**	-15.524**	-19.728**	-14.536**	-28.970**	-7.115**
15	BAU-06-05 x RL26018	-17.784**	19.472**	-13.813**	14.063**	13.049**	19.922**	-13.767**	-8.190**	13.235**	48.077**
16	BAU-06-05 x NL260	0.000	45.315**	-3.188**	28.125**	0.366	6.468**	-13.965**	-8.401**	22.058**	59.615**
17	BAU-06-05 x SLS72	6.186**	54.303**	-4.368**	26.563**	8.537**	15.136**	-1.391	4.986**	39.264	82.115**
18	BAU-06-05 x Shekhar	-8.505**	32.955**	1.889*	34.844**	10.122**	16.818**	-8.175	-2.236**	12.794	47.500**
19	NDL2005-24 x RL26018	8.250**	57.303**	-45.336**	-27.656**	10.610**	17.335**	-14.476	-8.945**	6.323	39.038**
20	NDL2005-24 x NL260	7.477**	56.180**	-46.045**	-28.594**	11.829**	18.629**	-16.492	-11.091**	9.264	42.885**
21	NDL2005-24 x SLS72	6.959**	55.427**	-40.260**	-20.938**	7.683**	14.230**	-4.882	1.269	16.176	51.923**
22	NDL2005-24 x Shekhar	11.343**	61.798**	-55.490**	-41.094**	6.463**	12.937**	-13.369	-7.767**	2.5	34.038**
23	RL26018 x NL260	-3.093**	40.820**	-0.826	31.250**	15.854**	22.898**	-10.275	-4.473**	55.882	103.846**
24	RL26018 x SLS72	-38.143**	-10.112**	-12.987**	15.156**	13.415**	20.310**	-0.426	6.014**	17.647	53.846**
25	RL26018 x Shekhar	0.518	46.067**	2.715**	35.938**	11.341**	18.111**	-8.402	-2.478**	58.235	106.923**
26	NL260 x SLS72	27.063**	84.640**	1.181	33.906**	10.610**	17.335**	-1.135	5.258**	75.441	129.423**
27	NL260x Shekhar	16.238**	68.910**	-4.723**	26.094**	11.829**	18.629**	-6.330	-0.272	69.558	121.731**
28	SLS72 x Shekhar	1.809*	47.944**	-45.336**	-27.656**	-15.854**	-10.737**	-0.085	6.377**	36.323	78.269**

and = Significant at 0.05 and 0.01 levels, respectively*

parents and crosses for their further use in the breeding programme. The estimate of GCA effects among the parental lines for yield and it's component traits to identify the best parent for subsequent hybrid development programme Table 3. The estimates of GCA effects revealed that good general combiner for seed yield per plant was SLS 72. In addition to the above trait, SLS72 was also found good general combiner for earliness, a number of capsule per plant, dwarfness and oil percent. The character wise estimation of GCA effects of parental genotypes revealed that the parents NL260 and Shekhar were the good general combiner for a number of capsules per plant while BAU-06-05 and RL26018 were the better general combiner for tallness. The parents PKDL71 and Shekhar were found good combiner for dwarfness while, NDL-2005-24 for early maturity. This result indicates the preponderance of additive and additive x additive gene effects [9,15]. Since the 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 programmes to accumulate their favourable genes responsible for increasing seed yield in promising pure lines. Data on GCA effects indicated that effects varied significantly for different characters in different parents. Good general combining parent results in a higher frequency of heterotic hybrids than the poor combining parent [16]. The high GCA effects in a desirable direction for yield and its contributing traits indicated that such lines would combine well with other lines to produce superior progeny.

Based on GCA effects the parental genotypes SLS72, NL260, Shekhar, NDL-2005-24 and PKDL71 could be utilised in multiple crossing programs involving all possible combinations followed by bi-parental mating to exploit the maximum variability towards the development of high yielding early maturing linseed varieties. It was reported earlier by Kumar et al. [17], Nie et al. [18] and Singh et al. [8] that cultivars with high individual GCA effects can be utilised in breeding programs for producing a relatively higher percentage of superior yielding progeny. Singh et al. [8] also reported that good general combiner plays an important role in developing population through crossing among them in all possible combinations. Abdel Moneam [19] and Kumar et al. [20] also recommended utilising 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 [9]. Diallel selective mating system [21] and recurrent selection schemes will be most effective breeding procedures which help in accumulating desirable alleles within the base populations. Singh et al. [8] supported the role of diallel selective mating for multiple crossing which produces an elite population for selection of high yielding lines in advanced generations.

3.2 SCA Effect

Sprague and Tatum [15] reported that the SCA effect is due to non-additive genetic proportion. The estimates of specific combining ability (SCA) effects for all the nine traits presented in Table 4. In general, the SCA effects do not contribute tangibly to the improvement of self-fertilising crops, except where commercial exploitation of heterosis is feasible. The SCA value represents the dominance and epistatic interactions which are non-fixable and related to heterosis [9]. 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 [17,18,22,8].

Among the hybrids, PKDL71 x LCK7035 (4.166) showed highest significant SCA effects in a positive direction for seed yield per plant followed by NL260 x SLS72 (2.616), NL260 x Shekhar (2.533) and LCK7035 x BAU-06-05 (2.10). The hybrid PKDL71 x LCK7035 also exhibited significant positive SCA effects for plant height, number of primary branches per plant, number of capsules per plant and days to maturity, indicating the potential for exploiting hybrid vigour in the breeding programme. Out of 28 crosses, seven crosses, i.e., LCK7035 x NDL2005-24, LCK7035 x NL260, PKDL71 x Shekhar, LCK7035x SLS72, PKDL71 x RL26018, BAU-06-05 x NL260 and BAU-06-05 x Shekhar showed significant and negative SCA effects for days to 50% flowering 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 the contribution of favourable alleles from their parents. For plant height, significant negative SCA effects were observed in the crosses NDL2005-24 x Shekhar, LCK7035x SLS72 and LCK7035 x BAU-06-05 as a best hybrid combination for short stature plants. For a number of primary branches per plant, crosses NL260 x SLS72, NL260x Shekhar, PKDL71 x LCK7035and PKDL71 x LCK7035 gave significant and positive SCA effects indicating that these crosses were the best combinations for this trait. For a number of capsules per plant, out of twenty-eight cross combinations, twenty crosses showed highly significant and positive SCA effects for a number of capsules per plant. The hybrids PKDL71 X LCK7035 showed highest significant SCA effect for a number of capsules per plant followed by NL260 x SLS72, NL260 x Shekhar and NDL2005-24 x RL26018 while, the hybrid PKDL71 x NL260 for oil percent. It was interesting to note that most of the prominent crosses were found to be common for a number of capsules per plant, number of primary branch per plant and grain yield per plant having positive and significant SCA values suggesting that these cross combinations could be successfully exploited for further yield improvement in linseed. 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. [23] also observed significant SCA effects revealing the meaningful contribution of additive and non-additive gene action for different traits in a diallel cross using eight flax genotypes. Abdel-Moneam [19] reported that most of the superior cross having significant SCA effect values for a particular trait include at least one of their parents of high GCA effects for the same trait.

The percentage of heterosis over better parent and check parent for seed yield and its component characters are presented in Table 5. The estimates of heterosis showed that none of the hybrids was found to be significantly high heterosis for all the characters. Earliness and 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 -27.31(NDL2005-24 x Shekhar) to 6.15% (BAU-06-05 x RL26018) over better parent and 8.00 (NDL2005-24 x Shekhar) to 51.43% (PKDL71 x BAU-06-05) over the standard check. Most of the crosses exhibited significant and negative heterosis for days to 50% flowering. Heterosis over better parent ranged from -2.14 (RL26018 x Shekhar) to 14.52 (LCK7035 x NDL2005-24) and -0.43 to 12.65 percent (LCK7035 x NDL2005-34 over check, respectively. In linseed, short stature with a vigorous structure containing more number of branches provide an opportunity for more yields, so positive heterosis is desirable for a number of primary branches. Heterosis estimates over better parent showed that out of 28 crosses, four crosses showed positive significant heterosis and the values of heterobeltiosis ranged from -49.16 (LCK7035 x NL260) to 12.19% (NL260 x SLS72) whereas, 11 crosses showed positive significant heterosis over check parent for number of primary branches, and the standard heterosis varied from -33.81 (LCK7035 x NL260) to 46.03 (NL260 x SLS72) respectively. Concerning a number of capsules per plant heterosis over better parent ranged from -54.12 (LCK7035 x NDL2005-24) to 27.06 (NL260 x Shekhar). Some capsules per plant are known to directly associate with grain yield and for this trait, cross NL260 x SLS72, PKDL x LCK7035, NL260 x Shekhar and NDL2005-24 x Shekhar showed significantly high per cent standard heterosis, whereas cross NL260 x Shekhar, showed significantly high % better parent heterosis. A number of seeds per capsule are also an important yield component trait associated with higher seed yield in linseed, Crosses RL26018 x Shekhar and PKDL71 x LCK7035 indicated significant positive heterosis over check parent and the cross RL26018 x Shekhar showed significant positive heterosis over the better parent. 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 the better parent. For 1000-grain weight out of 28 crosses, 20 and 24 crosses showed significant positive heterosis over better parent and checked parent respectively. The magnitude of heterosis for 1000-seed weight was found the maximum for the cross combination LCK7035 x NDL2005-24 (16.22% over mid-parent and 23.28% over better parent), respectively. With respect to oil content, the magnitude of heterosis varied from -16.49% (NDL2005 x NL260) to 19.72% (BAU-06-05 x NDL2005-24) and -14.53% (BAU-06-05 x NDL2005-24) to 7.79% (PKDL71 x SLS72) over better parent and check parent, respectively. The magnitude of heterosis for grain yield per plant varied from -28.97% (BAU-06-05 x NDL2005-24) to 75.44% (NL260 x Shekhar) and -7.11% (BAU-06-05 x NDL2005-24) to 129.42% (NL260 x SLS72) over better parent and check parent, respectively. The crosses NL260 x SLS72, PKDL71 x LCK7035, NL260 x Shekhar and RL26018 x NL260 exhibited significant positive standard heterosis for seed yield per plant which could be an excellent source for developing high yielding linseed genotypes. Heterosis for yield was reflected through heterosis in yield components especially number of capsules plant confirming the earlier findings of many workers reported a high degree of heterosis for seed yield in linseed *viz.,* Foster et al. [24]; Kurt and Evans [25]; Reddy et al. [26].

4. CONCLUSION

The estimates of GCA effects revealed that good general combiner for seed yield per plant was SLS 72. In addition to the above trait, SLS72 was also found good general combiner for earliness, a number of capsule per plant, dwarfness and oil percent. The character wise estimation of GCA effects of parental genotypes revealed that the parents NL260 and Shekhar were the good general combiner for a number of capsules per plant while BAU-06-05 and RL26018 were the better general combiner for tallness. The parents PKDL71 and Shekhar were found good combiner for dwarfness while, NDL-2005-24 for early maturity. The hybrid PKDL71 x LCK7035 was the best specific combination for seed yield per plant followed by NL260 x SLS72, NL260 x Shekhar and LCK7035 x BAU-06-05. These hybrids also showed significant positive SCA effects for plant height, secondary branches per plant, number of capsules per plant, indicating the potential for exploiting hybrid vigour in the breeding programme. Heterosis was worked out over better parent and check parent, for grain yield per plant and the crosses, NL260 x SLS72, PKDL71 x LCK7035, NL260 x Shekhar and RL26018 x NL260 exhibited significant positive standard heterosis for seed yield per plant which could be an excellent source for developing high yielding linseed genotypes. Hence, these crosses would be exploited for isolating transgressive segregants for seed yield and its related traits for genetic improvement in linseed.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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