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HETEROSIS AND COMBINING ABILITY VIA LINE × TESTER ANALYSIS FOR QUALITY AND SOME AGRONOMIC CHARACTERS IN SAFFLOWER

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ABSTRACT

This research was conducted in 2018 and 2019 at Tekirdag Namık Kemal University, Faculty of Agriculture, Field Crops Department, Research and Experimental area. It was aimed to determine general combining abilities (GCA) of parental lines, specific combining abilities (SCA) of hybrids, having F_1 hybrids from 5 female lines and 9 male testers. For this purpose, lines and testers were hybridized in all combinations using line x tester method in 2018. The field experiments for hybrids (F_1) were designed in a randomized complete block with three replications in 2019. The male parents Linas as high general combiners for developing increased seed and oil yields in safflower hybrids. The highest heterosis for oil content was calculated EC18 hybrid (14.281%). The highest heterosis was calculated in EC2 (34.079%) and EC4 (34.548%) for seed and oil yield, respectively. In the study, similar heterotic effect was observed between seed and oil yield as there is interaction between them. Hybrid EC2, EC4 and EC18 were determined as best combinations for high seed yield, oil content and oil yield according to the SCA and heterosis values. The promising hybrids will be grown in the next generations together with the other hybrids in order to ensure sufficient variation, and the selection will be started in the later generations such as F_3 and F_4.

Key words: *Carthamus tinctorius* L., Combining ability, Heterosis, Line x tester, Safflower

INTRODUCTION

Safflower (*Carthamus tinctorius* L.), which is from the *Asteraceae* family, started to be cultivated 3000 years ago and is one of the oldest cultivated plants. It contains 25-45% oil in its seeds, has two different types as linoleic (omega 6) and oleic (omega 9), has high quality edible oil, is suitable for biodiesel production, is cultivated in the form of residue and mixture and is considered as animal feed (Arslan et al., 2012; Culpan, 2015). On the other hand, drought tolerant and cultivation without irrigation enable especially availability of fallow areas (Arslan and Culpan, 2018). The oil content and seed yield of safflower are lower than other oil crops (soybean, sunflower, canola etc.), so safflower cultivation has not been able to develop both in Turkey and in the world. Therefore, various studies (selection and hybridization etc.) must be done in order to improve and increase seed yield and oil content especially and breeding studies must be conducted in order to develop new genotypes.

Suitable choice of parent based on their combining ability effects is crucial for the breeding studies. SCA (specific combining ability) of agronomic traits is an important and useful marker of the potential of inbred lines in generating successful hybrid combinations (Huang et al., 2010). General combining ability (GCA) is a measure of additive gene action, whereas SCA is related to dominance (Huang et al., 2010; Wang et al., 2010).

Line x tester method is widely used in quantitative trait inheritance studies. The method developed by Kempthorne in 1957 is one of the breeding strategies for estimates the GCA of parents and selecting of suitable parents and hybrid with high SCA (Kose, 2017). Heterosis or hybrid vigor describes the phenomenon in which hybrids formed between individuals of the same or closely related species are more vigorous than their parents (Timberlake, 2013).

Combining ability and heterosis are one of the most important characteristics for breeding improved new genotypes (Kose, 2017). Some researchers have studied the combining abilities and heterosis of safflower hybrid genotypes by using line x tester method for breeding characters (Ranga, 1982; Manjare and Jambhale, 1995; Golkar et al., 2012; Nai et al., 2014; Kose, 2017; Kanoje et al., 2018).

The aim of this study was to determine general combining abilities of parent lines, specific combining abilities and heterotic performance of hybrids. In addition, the main objectives of this research were to identify of suitable hybrids for the development of new lines and cultivars with high seed yield, oil content and oil quality.

MATERIALS AND METHODS

Location of experiment, soil and climate properties

The study was carried out between 2018 and 2019 at area of research and experiment, Field Crops Department, Faculty of Agriculture, Tekirdag Namik Kemal University (40°59'25.1"N 27°34'49.1"E) in Turkey. The soil of the experimental area was clayey (C), slightly alkaline (pH=7.10), and had sufficient phosphorus, rich in potassium but low in organic matter (1.33 %). The total rainfall at growing period of safflower (April to August) was 196 mm and mean monthly temperature 20.5 °C in experimental area in 2019. In this context, the soil and climate properties of the experimental area are sufficient and suitable for safflower.

Experimental design and measurements

Five selected lines [3 (PI 209287), 21 (PI 369842), 25 (PI 506427), 28 (PI 537601), Dincer] and nine testers [1 (PI 193473), 10 (PI 253520), 29 (PI 560161), 30 (PI 560177), 31 (PI 572432), 35 (PI 603208), Balci, Linas and Olas] were used for the important breeding objectives such as seed yield and oil content. Especially, safflower genotypes with high oil content; 29, 30, 31, 35, Balci, Linas and Olas were used as testers in the study. These lines and testers were obtained from Eskisehir Transitional Zone Agricultural Research Institute (Dincer and Balci), Trakya Agricultural Research Institute (Linas and Olas) and United States Department of Agriculture (USDA) Agricultural Research Service (PI coded). In this study, spininess was used as a morphological marker. Because spininess of safflower was controlled by single dominant gene and the spiny phenotype was wholly dominant to spineless (Pahlavani et al., 2004; Golkar et al., 2010). The lines (spineless) and testers (spiny) were used as female and male plant materials were hybridized through chemical male sterility (*ch-ms*) with gibberellic acid (GA_3) in June, 2018 (Baydar and Gokmen, 2003; Gokmen, 2004). Thus, 45 hybrid combinations were produced with the line x tester method (Table 1). The seeds obtained from each crossed head were harvested separately on August 1, 2018 and stored in the refrigerator at +4°C.

Table 1. Hybrid combinations of male and female genotypes

Parents		Lines (♀)				
		3	**21**	**25**	**28**	**Dincer**
Testers (♂)	**1**	3 x 1 (**BA1**)	21 x 1 (**BA7**)	25 x 1 (**BA13**)	28 x 1 (**BA19**)	D x 1 (**EC13**)
	10	3 x 10 (**BA2**)	21 x 10 (**BA8**)	25 x 10 (**BA14**)	28 x 10 (**BA20**)	D x 10 (**EC14**)
	29	3 x 29 (**BA3**)	21 x 29 (**BA9**)	25 x 29 (**BA15**)	28 x 29 (**BA21**)	D x 29 (**EC15**)
	30	3 x 30 (**BA4**)	21 x 30 (**BA10**)	25 x 30 (**BA16**)	28 x 30 (**BA22**)	D x 30 (**EC16**)
	31	3 x 31 (**BA5**)	21 x 31 (**BA11**)	25 x 31 (**BA17**)	28 x 31 (**BA23**)	D x 31 (**EC17**)
	35	3 x 35 (**BA6**)	21 x 35 (**BA12**)	25 x 35 (**BA18**)	28 x 35 (**BA24**)	D x 35 (**EC18**)
	Balci	3 x B (**EC1**)	21 x B (**EC4**)	25 x B (**EC7**)	28 x B (**EC10**)	D x B (**EC19**)
	Linas	3 x L (**EC2**)	21 x L (**EC5**)	25 x L (**EC8**)	28 x L (**EC11**)	D x L (**EC20**)
	Olas	3 x O (**EC3**)	21 x O (**EC6**)	25 x O (**EC9**)	28 x O (**EC12**)	D x O (**EC21**)

The seeds of hybrid (F_1) and their parents were sown by hand on April 19, 2019. The field experiments were designed in a randomized complete block with three replications. Each hybrid seeds were sown in plots with 2 rows; plots were 5 m long, with 50 cm between rows. Nitrogen and phosphorous were applied at the rate of 100 kg N (urea) and 60 kg P (DAP) per hectare, respectively. All phosphorus and half of the nitrogen were applied prior to seed sowing, and the remaining nitrogen was applied in stem elongation stage (about 1.5 months after sowing). Plants that were found to be spineless during the flowering period (non-hybrids) were cut off from the rows so that real hybrids remained in the rows. Ten plants per plot were selected randomly from each of the hybrids and parents for investigation yield components. These characters were plant height (cm), branch number per plant, head number per plant, head diameter (cm), number of seeds per head, 1000 seed weight (g), seed yield (kg ha^{-1}), hull content (%), oil content (%), oil yield (kg ha^{-1}), linoleic and oleic acid content (%). The all hybrids and parent plants were harvested by hand on August 5, 2019. The oil content analyzes of seeds were measured by reading in the Nuclear Magnetic Resonance (NMR) device as percentage. The seeds were dehumidified by keeping them in an oven at 70 ºC for 48 hours. The average oil content was calculated by making three readings in each plot on a 4 g seed NMR device (Erbas, 2012; Arslan and Culpan, 2020). The oil yield was calculated based on oil percentage and seed yield results (Goksoy et al., 2020). The fatty acid composition (linoleic and oleic acid) of hybrids and parents were analyzed in Gas Chromatography (Agilent 7820A GC) device.

Statistical analysis

The data of this study were analyzed with the TARPOPGEN software developed by Ozcan and Acikgoz (1999). The GCA variance effects of the parents and the SCA variance effects of the hybrids were calculated by the using of the line x tester method as described by Kempthorne (1957) and Singh and Chaudhary (1977):

$$g_i = y_{i.} - y_{..}$$

$$s_{ij} = y_{ij} - y_{..} - g_i - g_j$$

where g_i and g_j are the GCA effects for *i*-th and *j*-th lines, respectively; s_{ij} is the SCA effect for *ij*-th hybrid; y_{ij} is the trait value of *ij*-th hybrid; $y_{i.}$ is the average of the hybrids among i-th line crossed with a series of parents; $y_{i..}$ is the overall mean.

Heterosis was estimated based on two criteria, mid-parent heterosis (H_t) and high-parent heterosis (H_b), using the following formulae:

$$H_s\ (\%) = 100 \times (F_1 - MP)/MP$$

$$H_b\ (\%) = 100 \times (F_1 - HP)/HP$$

where F_1 is the mean performance of F_1 hybrids, MP is the parental mean, and HP is higher parent values for all tested traits. Heterotic effects were tested by the LSD test at the 0.05 and 0.01 levels. The *t*-test was used in order to determine the significance of GCA and SCA effects at 0.05 and 0.01 level.

RESULTS AND DISCUSSION

General combining ability (GCA)

The results of the variance analysis for line x tester population were given in Table 2a and Table 2b. The parents and hybrids showed significant differences according to the traits studied in the research. The lines used in the study showed a variation in terms of seed yield, oil content, oil yield and oleic acid content while the testers showed significant differences for seed yield and all quality traits. In addition, the interaction between lines and testers were indicated as significant for all traits except branch numbers ($p<0.01$).

Table 2a. Variance analysis of yield components for combining ability

SV		DF	Plant height	Branch number	Head number	Head diameter	Number of seeds per head	1000 seed weight
Replication	MS	2	0.789	0.159	3.637	0.010	28.350	13.3032
	F		2.962	1.459	2.433	1.395	11.617**	21.048**
Genotypes	MS	58	35.807	4.948	29.067	0.233	218.408	93.360
	F		134.333**	45.307**	19.443**	31.875**	89.495**	147.712**
Parents	MS	13	33.598	1.739	14.494	0.141	182.439	72.437
	F		126.047**	15.928**	9.695**	19.249**	74.756**	114.609**
Hybrids	MS	44	36.6780	5.669	26.700	0.266	233.813	97.916
	F		137.598**	51.919**	17.859**	36.264**	95.807**	154.922**
Parents vs	MS	1	26.222	14.891	322.668	0.021	8.204	164.863
Hybrids	F		98.375**	136.356**	215.825**	2.284	3.362	260.843**
Lines	MS	4	27.402	4.919	12.023	0.175	109.265	94.022
	F		0.748	1.069	0.446	0.611	0.383	0.878
Testers	MS	9	41.545	10.307	33.009	0.224	89.228	63.245
	F		1.134	2.239	1.224	0.781	0.313	0.591
Lines x	MS	32	36.620	4.604	26.958	0.287	285.527	107.071
testers	F		137.382**	42.160	18.032**	39.207**	116.998**	169.406**
Error		116	0.266	0.109	1.495	0.007	2.4405	0.6320

Table 2b. Variance analysis of seed yield and quality traits for combining ability

SV		DF	Seed yield	Hull content	Oil content	Oil yield	Linoleic acid content	Oleic acid content
Replication	MS	2	67.867	0.455	0.311	3.410	0.657	0.129
	F		2.610	1.011	3.005	0.999	1.403	1.386
Genotypes	MS	58	2913.227	21.865	13.593	315.182	738.736	741.136
	F		112.026**	48.493**	131.170**	92.336**	1576.516**	7923.343**
Parents	MS	13	3378.519	47.324	19.939	351.491	905.795	986.967
	F		129.918**	104.955**	192.400**	102.973**	1933.033**	10551.472**
Hybrids	MS	44	2835.481	14.825	11.997	310.436	664.482	657.463
	F		109.036**	32.880**	115.768**	90.945**	1418.055**	7028.808**
Parents vs	MS	1	285.267	0.660	1.332	52.000	1834.103	1226.963
Hybrids	F		10.970**	1.465	12.855**	15.234**	3914.111**	13117.213**
Lines	MS	4	7275.759	4.661	20.226	842.989	41.573	35.833
	F		9.919**	0.482	6.313**	9.229**	0.715	0.914
Testers	MS	9	9023.117	40.534	43.058	920.543	3401.307	3441.293
	F		12.301**	4.192**	13.439**	10.078**	58.502**	87.767**
Lines x	MS	32	733.537	9.668	3.204	91.340	58.140	39.209
testers	F		28.208**	21.443**	30.916**	26.759**	124.076**	419.182**
Error		116	26.004	0.450	0.103	3.413	0.468	0.093

SV: source of variation, DF: degree of freedom, MS: mean square, F: F value. **: significant at P<0.01

GCA effects (general combining ability) of the lines and testers in terms of the yield components were shown in Table 3a. Among the parents the highest positive GCA effect were obtained by the lines 21 and tester 31 in terms of plant height, and difference no significant statistically ($p>0.05$). The GCA effects of lines and testers on the branch number were insignificant, these values varied from -1.037 (testers 30) and 1.390 (testers 1). The general combining ability of the all parents in terms of head number, head diameter, number of seeds per head and 1000 seed weight were insignificant statistically (Table 3a). The present results confirm the findings of Golkar et al. (2012), Kose (2017), Kanoje et al. (2018) and Thorat and Gawande (2021).

Table 3a. GCA effects (general combining ability) of the parents for the yield components

Source of variation	Plant height	Branch number	Head number	Head diameter	Number of seeds per head	1000 seed weight
			Lines			
3 (♀)	-0.259	-0.436	-0.860	0.035	-2.104	-2.701
21 (♀)	1.685	-0.366	-0.353	0.110	1.111	-0.719
25 (♀)	-0.037	0.075	0.936	-0.091	-1.652	2.292
28 (♀)	-1.000	0.104	0.173	0.011	2.789	0.225
Dincer (♀)	-0.389	0.623	0.103	-0.128	-0.144	0.902
			Testers			
1 (♂)	-1.600	1.390	1.121	0.045	3.010	0.365
10 (♂)	-1.167	1.030	2.155	-0.105	-0.090	-0.478
29 (♂)	1.367	-0.990	-1.912	0.077	-2.303	-1.398
30 (♂)	-0.767	-1.037	1.761	-0.088	0.470	-1.937
31 (♂)	3.667	-0.544	-0.385	-0.092	-4.363	2.144
35 (♂)	-1.233	-0.224	-0.199	-0.045	-1.556	-1.325
Balci (♂)	-0.633	-0.064	-2.159	0.237	3.104	-0.655
Linas (♂)	-0.233	0.176	-0.305	0.100	1.317	-1.141
Olas (♂)	0.600	0.263	-0.079	0.077	0.410	4.425
SE (for lines)	0.099	0.064	0.235	0.016	0.301	0.153
SE (for testers)	0.133	0.085	0.316	0.022	0.403	0.205

GCA effects of the parents in terms of the seed yield and quality traits were given in Table 3b. Among the lines and testers while 1, 21, 28, Dincer, Balci, Linas and Olas had positive GCA effects and statistically significant ($p<0.01$), remaining other lines and testers had negative GCA effects for seed yield. For oil content among the parents significant and positive GCA effects were observed to 28, 30, 31, 35, Linas and Olas respectively. Therefore, these parents can be considered a great line and tester for a safflower breeding program. In addition, line 21, 28, Dincer and tester 1, 29, 35, Balci, Linas and Olas had significant and positive GCA effects in terms of oil yield among the parents. Particularly male parents Linas as high general combiners for developing increased seed and oil yields in safflower hybrids. Although GCA was not significant when the linoleic and oleic acid content was examined for the lines, testers were showed negative and positive highly significant GCA. Among the testers 35 and Olas had significant and negative GCA effects for linoleic acid content. On the contrary, same testers had significant and positive GCA effects for oleic acid content (13.122 and 35.623, respectively). This is expected in terms of linoleic and oleic acid composition. Golkar et al. (2011) reported that GCA effects for linoleic acid showed a range from -8.27 to 2.75 in F_1. Ratnaparkhi et al. (2015a) indicated that GCA values ranged from -2.357 to 1.327 in terms of oleic acid content. Because of the parents used by the researchers were linoleic type, their results are different from the results of our study. The parents with high GCA can be used to develop lines and cultivars with high seed yield, oil content and oil quality.

Specific combining ability (SCA)

SCA effect is an important characteristic for estimating and choosing suitable and superior hybrid combinations. In the study on SCA effects of 45 hybrids for all the traits were given in Table 4a and 4b. The SCA effects of hybrids were significant in terms of all traits (Table 2a and 2b, $p<0.01$). Among the hybrids the highest positive SCA effect were observed by the EC4 (5.115) in terms of plant height. Insignificant SCA effect for branch number was observed in 12 hybrids (Table 4a). BA1 hybrid had the highest positively and significant SCA in terms of head number (6.993). While EC2 hybrid (20.924) exhibited the highest positively and significant SCA effects for number of seeds per head, BA9 (-14.179) showed the lowest significantly negative SCA effects in terms of 1000 seed weight. Patel et al. (2018) reported that the highest SCA value for number of seeds per head was determined as 9.27 in the line (4) × tester (3) mating design. This difference may be due to the line (5) × tester (9) mating design in our study. The SCA effects of hybrids on the seed yield were significant, these values varied from -35.563 (EC5) and 28.236 (BA19). Nai et al. (2014) reported that SCA effects for seed yield showed a range from -1.05 to 23.50 in 45 F_1 genotypes, Kanoje et al. (2018) indicated that SCA values ranged from -38.19 to 43.93 in terms of seed yield. It can be said that the differences in our study are the safflower line and testers used by other researchers.

Table 3b. GCA effects (general combining ability) of the parents for the seed yield and quality

Source of variation	Seed yield	Hull content	Oil content	Oil yield	Linoleic acid content	Oleic acid content
			Lines			
3 (♀)	-9.572**	-0.071	-1.086**	-4.226**	0.309	-0.084
21 (♀)	16.010**	-0.044	-0.053	5.085**	1.799	-1.464
25 (♀)	-23.376**	0.682	0.023	-7.559**	-1.635	1.287
28 (♀)	3.991**	-0.453	1.330**	2.460**	-0.382	-0.726
Dincer (♀)	12.947**	-0.114	-0.214**	4.240**	-0.092	0.987
			Testers			
1 (♂)	10.824**	-0.083	-2.572**	0.956*	6.592**	-9.105**
10 (♂)	-15.376**	2.124**	-2.390**	-7.029**	8.066**	-8.632**
29 (♂)	-9.516**	-0.473**	0.136	2.864**	10.337**	-9.085**
30 (♂)	-25.296**	-0.046	0.717**	-7.466**	0.995**	-1.259**
31 (♂)	-39.463**	-1.576**	1.227**	-11.787**	2.889**	-4.281**
35 (♂)	-0.136	-3.206**	2.901**	2.956**	-12.608**	13.122**
Balci (♂)	25.310**	1.594**	-0.335**	7.810**	10.245**	-8.438**
Linas (♂)	33.570**	0.527**	0.263**	11.560**	8.807**	-7.945**
Olas (♂)	20.084**	1.137**	0.053	5.863**	-35.325**	35.623**
SE (for lines)	0.981	0.129	0.062	0.356	0.132	0.059
SE (for testers)	1.317	0.173	0.083	0.477	0.177	0.079

SE: standard error, *: significant at P<0.05, **: significant at P<0.01

The more than half of the hybrid combination had positive SCA effect for oil content and oil yield. While the highest positive and significant SCA effect was observed by the EC18 (2.014) in terms of oil content, the highest positive and significant SCA effect for oil yield was obtained from the EC4 hybrid (9.441). Similar results were reported earlier by Kose (2017) and Kanoje et al. (2018). In addition, Thorat and Gawande (2021) determined that the SCA values ranged from -2.145 to 2.145 in terms of oil content. It can be said that the reason for this difference is that the genotypes used belong to different geographical origins. While the highest positive and significant SCA effect was observed by the BA24 hybrid (12.616) in terms of linoleic acid content, the lowest negative and significant SCA effect for oleic acid content was obtained from the same hybrid (-13.668). Selection for high SCA effects in terms of seed yield, oil content and oil yield would be a suitable strategy for improvement new safflower cultivars and lines. In addition, choosing hybrids with low hull content will contribute to the development of lines and varieties with low and thin hull.

Heterosis and heterobeltiosis

Heterosis (Ht) and heterobeltiosis (Hb) values of hybrids for the selected characters in the study were presented in Table 5. Significant heterosis and heterobeltiosis were found for different hybrids for the selected characters (seed yield, oil content and oil yield). The highest heterosis and heterobeltiosis were calculated EC2 (34.079%) and EC4 (26.200%) hybrids for seed yield, respectively. The heterosis and heterobeltiosis values ranged from -6.567% to 14.281% and -12.571% to 5.597% for the oil content, respectively. The highest heterosis was calculated EC18 hybrid (14.281%). The highest heterosis was calculated in EC2 (34.079%) and EC4 (34.548%) for seed and oil yield, respectively. In the study, similar heterotic effect was observed between seed and oil yield as there is interaction between them. Ranga (1982) calculated the heterosis value as 55.0% in terms of seed yield in the F_1 hybrid. Ratnaparkhi et al. (2015b) calculated the heterosis values in terms of oil content -22.70% and -4.04%. Erbas (2012) calculated the heterosis value as 42.3% in terms of oil yield. The difference in the heterosis and heterobeltiosis results of different researchers studied in the present line and testers can be commented to the divergence of the material used in studies.

Heterosis touches on the phenomenon that lineage of diverse varieties of a species or crosses between species present more yield, development, and fertility than both parents (Birchler et al., 2010). Heterosis and heterobeltiosis values are crucial and considerable genetic parameters for plant breeding programs. These values are guidelines for selecting superior hybrids.

Table 4a. SCA effects (specific combining ability) of the hybrids for the yield components

Code	Hybrids	Plant height	Branch number	Head number	Head diameter	Number of Seeds per head	1000 seed weight
BA1	3 x 1	0.693*	-0.030	**6.993****	-0.211**	-5.270**	-6.603**
BA2	3 x 10	-3.074**	-1.837**	-0.273	-0.227**	-7.770**	2.330**
BA3	3 x 29	2.226**	-0.050	0.493	-0.300**	-9.656**	8.323**
BA4	3 x 30	-3.141**	0.130	**-4.647****	0.238**	5.270**	3.443**
BA5	3 x 31	1.093**	-0.564**	-3.200**	**0.527****	16.370**	0.445
BA6	3 x 35	3.659**	1.583**	-1.620*	-0.229**	-5.170**	-1.083*
EC1	3 x B	-4.107**	0.990**	0.640	-0.083	-9.996**	-2.949**
EC2	3 x L	-0.174	-1.150**	-0.547	0.308**	**20.924****	-6.120**
EC3	3 x O	2.826**	0.930**	2.160**	-0.022	-4.703**	2.214**
BA7	21 x 1	4.248**	-0.234	-1.214	-0.202**	-9.818**	0.198
BA8	21 x 10	-1.019**	1.326**	2.553**	0.245**	11.716**	9.598**
BA9	21 x 29	-3.885**	0.546**	-0.181	-0.008	-3.971**	**-14.179****
BA10	21 x 30	-7.585**	-0.641**	-4.254**	0.490**	11.022**	-4.229**
BA11	21 x 31	-1.185**	-0.301	0.693	0.042	6.889**	-5.637**
BA12	21 x 35	0.715*	0.713**	1.606*	-0.124*	-8.784**	6.515**
EC4	21 x B	**5.115****	-0.781**	0.166	-0.141**	-1.011	1.239**
EC5	21 x L	3.715**	-0.687**	-0.354	-0.273**	-11.124**	2.871**
EC6	21 x O	-0.119	0.059	0.986	-0.030	5.082**	3.625**
BA13	25 x 1	-0.030	0.725**	1.030	0.209**	1.312	5.777**
BA14	25 x 10	-0.130	0.785**	0.797	-0.077	-0.421	-5.093**
BA15	25 x 29	2.837**	0.805**	-0.703	0.230**	10.192**	-2.489**
BA16	25 x 30	4.637**	-0.681**	3.924**	-0.022	-0.881	0.233
BA17	25 x 31	2.037**	1.492**	1.370	-0.140**	-8.348**	-0.428
BA18	25 x 35	**-6.396****	-1.195**	-3.150**	0.381**	14.745**	0.221
EC7	25 x B	2.170**	0.079	1.810*	0.030	-0.615	2.385**
EC8	25 x L	-1.063**	-0.495**	-3.876**	-0.285**	-2.995**	-3.566**
EC9	25 x O	-4.063**	-1.515**	-1.203	-0.325**	**-12.988****	2.961**
BA19	28 x 1	-1.400**	**-2.071****	-4.107**	0.503**	6.038**	-1.972**
BA20	28 x 10	1.333**	-0.411**	-3.673**	-0.176**	-5.762**	-4.216**
BA21	28 x 29	-3.867**	-0.491**	-0.807	0.114*	5.384**	-1.256**
BA22	28 x 30	1.933**	0.822**	0.920	-0.245**	-11.222**	5.747**
BA23	28 x 31	-0.500	0.462**	0.033	-0.366**	-8.989**	5.199**
BA24	28 x 35	3.233**	0.942**	4.713**	0.228**	4.304**	-3.496**
EC10	28 x B	-0.700*	0.049	-2.260**	-0.326**	1.111	-0.632
EC11	28 x L	-0.100	**2.242****	5.153**	0.015	2.864**	-2.112**
EC12	28 x O	0.067	-1.544**	0.027	0.252**	6.271**	2.738**
EC13	D x 1	-3.511**	1.610**	-2.703**	-0.300**	7.738**	2.601**
EC14	D x 10	2.889**	0.137	0.597	0.234**	2.238**	-2.619**
EC15	D x 29	2.689**	-0.810**	1.197	-0.036	-1.949*	**9.601****
EC16	D x 30	4.156**	0.370	4.057**	**-0.461****	-4.189**	-5.193**
EC17	D x 31	-1.444**	-1.090**	1.104	-0.063	-5.922**	0.422
EC18	D x 35	-1.211**	-2.043**	-1.550*	-0.255**	-5.096**	-2.156**
EC19	D x B	-2.478**	-0.336	-0.356	0.521**	10.511**	-0.042
EC20	D x L	-2.378**	0.090	-0.376	0.235**	-9.669**	8.927**
EC21	D x O	1.289**	2.070**	-1.970**	0.125*	6.338**	-11.539**
SE		0.298	0.191	0.706	0.049	0.902	0.459

SE: standard error, *: significant at P<0.05, **: significant at P<0.01

Table 4b. SCA effects (specific combining ability) of the hybrids for the seed yield and quality

Code	Hybrids	Seed yield	Hull content	Oil content	Oil yield	Linoleic acid content	Oleic acid content
BA1	3 x 1	-18.268**	-0.579	-0.858**	-5.147**	0.885*	-0.286
BA2	3 x 10	-1.301	0.948*	0.420*	0.738	-1.079**	-1.070**
BA3	3 x 29	-9.028**	-1.172**	0.724**	-2.047	-0.561	1.284**
BA4	3 x 30	-14.515**	**3.568****	-1.351**	-5.009**	-1.668**	-2.902**
BA5	3 x 31	15.352**	-1.585**	0.206	5.526**	-2.053**	1.130**
BA6	3 x 35	1.125	0.861*	0.216	0.506	-1.275**	3.036**
EC1	3 x B	1.612	-1.105**	0.214	0.452	0.401	-0.084
EC2	3 x L	22.185**	-0.639	-0.103	5.965**	2.710**	-0.924**
EC3	3 x O	2.839	-0.299	0.533**	-0.985	2.641**	-0.184
BA7	21 x 1	16.117**	2.394**	0.685**	5.421**	-1.695**	0.934**
BA8	21 x 10	-3.350	2.120**	-0.500**	-1.950	0.031	2.021**
BA9	21 x 29	17.324**	-0.050	0.407*	6.001**	-0.010	-0.096
BA10	21 x 30	0.370	-0.310	-0.484*	-0.283	1.342**	-1.502**
BA11	21 x 31	-4.330	-1.413**	0.259	-1.035	0.378	0.450*
BA12	21 x 35	2.410	-0.816*	-0.794**	0.331	0.435	0.467**
EC4	21 x B	24.697**	-2.450**	1.158**	**9.441****	-1.422**	-0.183
EC5	21 x L	**-35.563****	2.367**	-0.196	**-12.179****	-3.480**	3.623**
EC6	21 x O	-17.676**	-1.843**	-0.537**	-5.746**	4.422**	-5.714**
BA13	25 x 1	-5.564	-1.216**	0.750**	-0.741	0.939*	-1.267**
BA14	25 x 10	7.936**	0.044	0.928**	3.721**	1.505**	-1.940**
BA15	25 x 29	-9.458**	0.841*	-0.671**	-3.401**	-0.210	-0.827**
BA16	25 x 30	7.089*	0.148	0.504**	2.171*	-3.404**	2.217**
BA17	25 x 31	6.989*	-0.256	-0.279	2.042	-2.692**	0.439*
BA18	25 x 35	-2.671	-2.559**	0.561**	-0.974	-3.591**	**6.546****
EC7	25 x B	-7.618*	2.008**	-1.471**	-3.848**	1.015*	-0.794**
EC8	25 x L	-12.378**	-0.376	-0.585**	-5.008**	-0.353	-2.678**
EC9	25 x O	15.676**	1.364**	0.265	6.038**	6.792**	-1.695**
BA19	28 x 1	**28.236****	0.420	-0.381*	7.877**	-4.254**	1.546**
BA20	28 x 10	2.302	-1.070**	1.211**	1.822	-2.658**	1.700**
BA21	28 x 29	-0.224	-0.974*	1.438**	1.470	0.131	0.616**
BA22	28 x 30	-13.944**	**-2.700****	0.370*	-4.528**	-4.473**	5.100**
BA23	28 x 31	-21.011**	0.430	-0.443*	-7.627**	2.319**	-1.068**
BA24	28 x 35	-3.138	0.860*	-1.997**	-3.150**	**12.616****	**-13.668****
EC10	28 x B	-4.118	0.676	0.139	-0.771	0.263	1.869**
EC11	28 x L	14.022**	-0.024	-0.052	4.846**	2.222**	0.066
EC12	28 x O	-2.124	2.383**	-0.286	0.059	-6.167**	3.838**
EC13	D x 1	-20.520**	-1.019**	-0.196	-7.410**	4.126**	-0.927**
EC14	D x 10	-5.587	-2.043**	**-2.058****	-4.331**	2.202**	-0.710**
EC15	D x 29	1.387	1.354**	-1.898**	-2.023	0.650	-0.977**
EC16	D x 30	21.000**	-0.706	0.961**	7.649**	8.203**	-2.913**
EC17	D x 31	3.000	2.824**	0.258	1.093	2.048**	-0.951**
EC18	D x 35	2.273	1.654**	**2.014****	3.287**	**-8.184****	3.619**
EC19	D x B	-14.573**	0.871*	-0.040	-5.274**	-0.258	-0.808**
EC20	D x L	11.733**	-1.329**	0.936**	6.376**	-1.099**	-0.088
EC21	D x O	1.287	-1.606**	0.025	0.633	-7.688**	3.755**
SE		2.944	0.388	0.186	1.067	0.395	0.177

SE: standard error, *: significant at P<0.05, **: significant at P<0.01

Table 5. Heterosis (H_t) and heterobeltiosis (H_b) values of hybrids for the selected characters

Code	Hybrids	Seed yield		Oil content		Oil yield	
		H_t	H_b	H_t	H_b	H_t	H_b
BA1	3 x 1	-11.576**	-24.723**	**-6.567****	-7.342**	-14.081**	-27.367**
BA2	3 x 10	1.362	-4.030	2.582**	-0.746	5.040	-3.598
BA3	3 x 29	-4.595	-6.287	0.105	-7.451**	-4.388	-10.143
BA4	3 x 30	-25.387**	-32.003**	-1.952*	-7.147**	-25.910**	-29.369**
BA5	3 x 31	14.650*	-13.018*	1.470	-6.539**	19.597*	-3.473
BA6	3 x 35	3.300	-7.733	4.191**	-5.948**	6.258	-13.236**
EC1	3 x B	15.380**	-5.736	2.405**	-0.626	17.344**	-6.338
EC2	3 x L	**34.079****	5.612	1.459	-3.202**	34.248**	2.176
EC3	3 x O	7.792*	-13.813**	-0.412	-7.656**	-3.143	-26.761**
BA7	21 x 1	17.119**	9.240**	-2.105*	-5.366**	16.083**	4.947
BA8	21 x 10	-1.953	-24.338**	-1.566	-8.540**	-5.589	-30.779**
BA9	21 x 29	19.975**	-4.828	-1.666*	-5.354**	19.185**	-2.590
BA10	21 x 30	-5.211**	-28.897**	0.005	-1.294	-4.278	-27.917**
BA11	21 x 31	-12.930**	-42.769**	0.771	-3.385**	-10.221	-39.720**
BA12	21 x 35	2.750	-8.897**	0.261	-5.883**	3.902	-2.241
EC4	21 x B	28.829**	**26.200****	4.477**	3.205**	**34.548****	**30.244****
EC5	21 x L	-14.466**	-16.767**	0.272	-0.260	-14.284**	-17.048**
EC6	21 x O	-9.475**	-10.142**	-4.468**	-7.764**	-13.490**	-17.046**
BA13	25 x 1	-2.488	-25.658**	-1.652	-4.934**	-3.023	-24.277*
BA14	25 x 10	10.270	1.217	3.546**	-3.795**	15.176*	13.634
BA15	25 x 29	-10.598	-20.685**	-4.721**	-8.290**	-15.260*	-27.324**
BA16	25 x 30	-1.335	-5.879**	3.319**	1.982*	0.783	-4.413
BA17	25 x 31	-4.798	-19.428**	-0.635	-4.730**	-4.555	-16.231*
BA18	25 x 35	-4.832	-24.469**	4.484**	-1.915**	-2.212	-25.936**
EC7	25 x B	3.979	-23.393**	-3.703**	-4.881**	0.596	-25.310**
EC8	25 x L	0.665	-28.038**	-0.718	-1.241	-0.269	-28.961**
EC9	25 x O	18.118**	-14.513**	-1.799*	-5.183**	14.525**	-18.882**
BA19	28 x 1	23.408**	20.638**	-2.362**	-6.754**	20.353**	12.509**
BA20	28 x 10	-2.062	-21.666**	7.483**	-1.285	3.017	-22.640**
BA21	28 x 29	-1.609	-18.961**	4.384**	1.706*	3.282	-13.093**
BA22	28 x 30	-26.420**	-42.899**	5.651**	**5.597****	-21.832**	-39.631**
BA23	28 x 31	**-40.809****	**-60.129****	1.584*	-1.412	**-38.941****	**-58.207****
BA24	28 x 35	-6.888	-13.713**	-0.399	-5.384**	-7.729*	-10.089**
EC10	28 x B	3.120	0.268	4.288**	1.747*	7.628*	7.241
EC11	28 x L	17.767**	9.369**	3.753**	3.001**	22.280**	14.291**
EC12	28 x O	-2.347	-7.582*	-0.713	-2.954**	-3.130	-10.256**
EC13	D x 1	-13.351**	-18.502**	0.510	-2.146*	-12.766**	-15.796**
EC14	D x 10	-5.920	-26.937**	-1.258	-2.695**	-7.535	-28.940**
EC15	D x 29	3.523	-17.330**	-3.804**	**-12.571****	2.156	-11.599**
EC16	D x 30	13.350**	-14.460**	10.325**	2.659**	28.868**	1.982
EC17	D x 31	-6.898	-38.540**	6.169**	-3.859**	4.455	-27.154**
EC18	D x 35	1.109	-9.644**	**14.281****	1.461	17.320**	16.437**
EC19	D x B	-2.057	-3.206	6.367**	1.372	4.233	0.472
EC20	D x L	18.180**	14.007**	9.649**	2.774**	34.067**	21.495**
EC21	D x O	3.037	1.376	2.482**	-6.586**	5.469	-5.231

* and **: significant at P<0.05 and P<0.01, respectively

CONCLUSIONS

Choice for lines and testers with high general combining ability effects and hybrids with high specific combining ability effects would be a suitable objective for high seed yield, oil content and oil quality in safflower. Especially hybrid EC2, EC4 and EC18 were determined as best combinations for high seed yield, oil content and oil yield according to the SCA and heterosis values. In addition, BA24 hybrid is promising for developing cultivars with high oleic acid content. The promising hybrids will be grown in the next generations together with the other hybrids in order to ensure sufficient variation, and the selection will be started in the later generations such as F_3 and F_4.

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