Genetic Analysis of Combining Ability and Gene action in Sunflower (*Helianthus annuus* L.) Hybrids through Line × Tester Design

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ABSTRACT

This study was conducted to evaluate the combining ability of six cytoplasmic male sterile (CMS) lines and nine testers using the line × tester method. Biometrical data were recorded for ten agronomic traits: days to 50% flowering, days to maturity, plant height, head diameter, seed filling percentage, 100-seed weight, volume weight, hull content, oil content, and seed yield per plant. The results indicated that specific combining ability (SCA) variance was higher than general combining ability (GCA) variance for most traits, except for days to 50 percent flowering and seed filling percentage, suggesting that non-additive gene action predominantly governed the inheritance of these traits. The GCA of parents did not always align with their per se performance, indicating that GCA should be the primary criterion for selecting parents in breeding programs. Three CMS lines, CMS-103A, CMS-10A and CMS-112A, along with testers EC-75717, EC-502036, EC-279309-1 and R-271-1, were identified as good general combiners for seed yield and yield-contributing traits. Among the hybrids, CMS-243A × EC-279309-1, CMS-243A × EC-75717 and CMS-103A × EC-75717 exhibited the highest SCA effects for seed yield per plant. These findings underscore the importance of selecting superior general combiners for traits like oil content and seed yield to develop high-yielding sunflower hybrids.

Keywords: Sunflower, line × tester, combining ability, seed yield, general combining ability, specific combining ability

1. INTRODUCTION

Sunflower (*Helianthus annuus* L.), a key member of the Asteraceae family, is the second most important oilseed crop globally, after soybean. It provides a rich source of edible oil, with 40-45% oil content, and is valued for its high levels of polyunsaturated fatty acids, particularly linoleic (55-60%) and oleic acids (25-30%), which are beneficial for heart health. In India, sunflower has significant potential for large-scale production, driven by advancements in breeding technologies and the development of high-yielding hybrids.

The success of sunflower hybrid breeding is largely dependent on selecting parental lines with desirable traits, which is assessed through combining ability. Combining ability includes two components: general combining ability (GCA) and specific combining ability (SCA). GCA measures a parent's average performance when crossed with multiple testers, typically reflecting additive gene action, which can be passed down to offspring. In contrast, SCA focuses on the performance of specific crosses, driven by non-additive gene action, such as dominance and epistasis.

In sunflower breeding, the line × tester analysis, proposed by Kempthorne (1957), is widely used to estimate GCA and SCA. This technique helps breeders to understand the gene action controlling key traits like seed yield, oil content, and disease resistance. It enables the identification of parental combinations with superior hybrid potential, allowing breeders to select lines for improved hybrid performance.

The present study was undertaken to evaluates the combining ability of six cytoplasmic male sterile (CMS) lines, nine fertility restorer and their newly developed sunflower hybrids. The

CMS lines are crucial in hybrid breeding since they eliminate the need for manual emasculation, while fertility restorer lines ensure successful seed production by restoring fertility in hybrids. High GCA in these parental lines is essential for breeding high-performing sunflower hybrids.

Additionally, the study explores the gene action behind traits like seed yield, oil content, and disease resistance. Traits governed by additive gene action, measured by GCA, can be improved through selection, while those influenced by non-additive gene action, reflected in SCA, require exploiting hybrid vigor or heterosis. Heterosis allows hybrids to outperform their parents, leading to superior agronomic performance.

Overall, this study aims to provide insights into the genetic potential of CMS and fertility restorer lines using line × tester analysis. Understanding both GCA and SCA allows breeders to develop efficient breeding strategies, ultimately leading to the production of high-yielding, disease-resistant sunflower hybrids. This will contribute to increased sunflower productivity and sustainability in Indian agriculture.

2. MATERIAL AND METHODS

The study was conducted at Oilseed Research Station, Latur, Maharashtra, during the *Rabi* seasons of 2023-24, to evaluate the combining ability of six cytoplasmic male sterile (CMS) lines (CMS-248A, CMS-243A, CMS-903A, CMS-112A, CMS-103A, CMS-10A) and nine fertility restorer lines (EC-75717, EC-502036, EC-279309-1, J/6, IR-1-1, RHA-1-1, MRHA-2-8, R-271-1, TSG298-R). The line × tester method was employed to generate 54 hybrid combinations, which were evaluated alongside 15 parental lines and three checks (LSFH-171, KBSH-44, LSF-08) in a randomized block design (RBD) with two replications during rabi 2023-24. Data were collected on traits including days to 50% flowering, days to maturity, plant height, head diameter, seed filling percentage, 100-seed weight, volume weight, hull content, oil content, and seed yield per plant. Statistical analysis was conducted using Kempthorne's line × tester method to estimate general combining ability (GCA) and specific combining ability (SCA), providing insights into the genetic potential of sunflower hybrids for yield improvement across diverse agro-climatic conditions.

3. RESULTS AND DISCUSSION

3.1Analysis of Variance for Combining Ability

The analysis of variance for combining ability across ten traits days to 50 per cent flowering, days to maturity, plant height, head diameter, seed filling, 100-seed weight, volume weight, hull content, oil content, and seed yield per plant — revealed significant variance in crosses for all traits. Line effects were significant for all traits except days to maturity and 100-seed weight, while tester effects were significant for all except these two traits as well. Line × tester interaction effects were significant for all traits except plant height, volume weight, and seed yield per plant. These findings align with results reported by Ingle et al. (2017) and Varalaxmi and Neelima (2019).

The estimates of variance components showed that SCA variance was greater than GCA variance for traits like days to maturity, head diameter, 100-seed weight, volume weight, hull content, oil content, and seed yield, indicating non-additive gene action for these traits, making them suitable for heterosis breeding. Conversely, GCA variance was larger than SCA variance for days to flowering and seed filling, suggesting the predominance of additive gene action, which can be exploited through pedigree breeding. These observations are consistent with findings from Shrishaila et al. (2017) and Thorat et al. (2018).

The GCA/SCA ratio greater than unity for days to flowering and seed filling suggests that additive gene action plays a key role in their inheritance, while a ratio less than unity for other traits highlights the importance of non-additive gene action. Similar conclusions have been reported by Kaya and Atkasi (2004), Khan et al. (2009), and Tabrizi et al. (2012), emphasizing the potential for heterosis breeding in traits governed by non-additive gene action.

3.2 Percent Contribution of Lines, Testers, and Line × Tester Interaction to Hybrid Sum of Squares

Table 1 shows the percent contribution of lines (females), testers (males), and their interaction to the hybrid sum of squares. For most traits, testers contributed more than lines, except for volume weight. The highest contributions by testers were observed in traits such as plant height (47.27%), oil content (53.94%), and hull content (50.95%). Line × tester interaction contributed significantly to 100-seed weight (66.19%), volume weight (59.68%), seed yield (52.55%), and days to maturity (46.53%), indicating that gene interactions play a major role in hybrid performance for these traits.

These results align with Kulkarni and Supriya (2017) for plant height and seed yield and Varalaxmi and Neelima (2019) for traits like days to flowering, seed filling, and oil content. The significant role of line × tester interaction suggests that non-additive gene action is crucial for traits such as seed yield and 100-seed weight, as also reported by Memon et al. (2015), Tyagi and Dhillon (2016), and Bhoite et al. (2018)

Table 1: Proportional contribution of lines, testers and line x tester in hybrids for different character in sunflower.

Character	Lines	Testers	L x T
Days to 50% flowering	28.87	43.83	27.3
Days to maturity	23.56	29.91	46.53
Plant height (cm)	43.33	47.27	9.4
Head diameter (cm)	15.99	39.58	44.44
Seed filling (%)	12.86	46.02	41.12
100 seed weight (g)	11.84	21.97	66.19
Volume weight (g/100ml)	21.56	18.77	59.68
Hull content (%)	13.01	50.95	36.05
Oil content (%)	13.48	53.24	33.28
Seed yield/ plant (g)	17.84	29.62	52.55

Table 2: Analysis of variance for combing ability for different characters in sunflower.

Characters	Df	Days to 50% flowering	Days to maturity	Plant height (cm)	Head diameter (cm)	Seed filling (%)	100 seed weight (g)	Volume weight (g/100ml)	Hull content (%)	Oil content (%)	Seed yield/ plant (g)
Replicates	1	0.593	0.593	84.058	2.513	2.654	0.009	2.083	0.284	0.096	10.653
Crosses	53	13.903 **	1.735 **	325.553 **	6.122 **	272.692 **	0.764 **	20.240 **	4.547 **	19.135 **	222.975 **
Line Effect	5	36.304 **	2.526	1495.085 **	10.375 *	869.043 **	0.959	46.254 *	6.269 *	27.338 *	421.541 *
Tester Effect	8	39.565 **	2.891	1019.518 **	16.051 **	806.555 **	1.112	25.162	15.345 **	67.493 **	437.497 *
Line * Tester Eff.	40	5.970 **	1.405 *	40.569	3.605 **	91.375 **	0.670 **	16.004 **	2.172 **	8.438 **	155.250 **
Error	53	1.14	0.744	83.466	1.034	2.195	0.038	0.989	0.423	0.228	9.177
Total	107	7.457	1.233	203.384	3.568	136.184	0.398	10.535	2.464	9.592	115.091
Estimates of variance components											
GCA		2.457	0.134	78.261	0.808	55.71	0.067	2.305	0.697	3.141	28.044
SCA		2.449	0.35	-21.408	1.253	44.611	0.317	7.433	0.908	4.071	73.194
GCA/SCA		1.003267	0.382857	-3.65569	0.644852	1.248795	0.211356	0.310104	0.767621	0.771555	0.383146

* Significant at 5 % level and ** significant at 1 % level.

3.3 General combining ability

The estimation of general combining ability (GCA) effects revealed significant insights into the genetic potential of sunflower parental lines for various agronomic traits. In terms of days to 50% flowering, CMS lines CMS-112A (-1.148) and CMS-103A (-1.981) demonstrated significant negative GCA effects, making them favorable for early flowering. Similarly, testers MRHA-2-8 (-3.787) and TSG-298R (-1.204) emerged as good combiners for earliness, while lines such as EC-502036 (1.630), EC-279309-1 (2.380), and RHA-1-1 (1.213) contributed to delayed flowering. These findings align with previous reports by Jan et al. (2005) and Khan et al. (2009), which indicated the importance of these lines in promoting early flowering and maturity in breeding programs. Additionally, CMS-112A and MRHA-2-8 were identified as the best general combiners for both early flowering and maturity, with CMS-112A (-0.574) and MRHA-2-8 (-0.769) also showing significant negative GCA effects for days to maturity.

For plant height, CMS-103A (-15.978) and restorer EC-75717 (-13.723) exhibited strong negative GCA effects, suggesting their potential for reducing plant height and promoting medium-tall genotypes with enhanced yield potential. These results are consistent with the findings of Farrokhi et al. (2008), who reported significant GCA effects in the desirable direction for plant height. In contrast, CMS-248A (8.727) and R-271-1 (11.318) displayed significant positive GCA effects, indicating their contribution to increased plant height.

Regarding head diameter, CMS lines CMS-10A (0.806) and CMS-112A (0.526), along with restorers EC-502036 (1.151) and R-271-1 (1.651), demonstrated significant positive GCA effects, making them excellent combiners for this trait. Negative GCA effects were observed in CMS-903A (-1.29) and MRHA-2-8 (-2.13). For seed filling percentage, lines CMS-10A (8.741) and CMS-103A (2.782), along with testers MRHA-2-8 (11.531), R-271-1 (8.835), and IR-1-1 (7.197), emerged as superior combiners. Conversely, CMS-248A (-9.826) and EC-502036 (-7.541) displayed negative GCA effects, reducing their suitability for seed filling improvement.

In terms of 100-seed weight, lines CMS-243A (0.234) and CMS-103A (0.202) were identified as strong positive combiners, along with testers EC-279309-1 (0.212) and R-271-1 (0.602). Negative GCA effects were recorded for CMS-248A (-0.382) and IR-1-1 (-0.170). Similarly, CMS-248A (1.731), CMS-243A (1.954), and testers MRHA-2-8 (1.898) and TSG-298R (1.565) showed positive GCA effects for volume weight, confirming their utility for this trait, consistent with findings from Patil et al. (2012) and Shinde et al. (2016).

For hull content, significant negative GCA effects were observed in CMS-243A (-0.788) and R-271-1 (-0.775), making them ideal for lowering hull content in breeding programs. CMS-243A (1.805) and tester EC-279309-1 (1.055) demonstrated positive GCA effects for oil content, while CMS-10A (-1.629) and RHA-1-1 (-4.295) had negative effects, highlighting their limited utility for improving oil content. These results align with earlier studies by Kaya (2005).

Lastly, seed yield per plant was significantly influenced by CMS lines CMS-103A (5.858) and CMS-10A (5.431), alongside testers EC-502036 (9.318) and R-271-1 (7.448), positioning them as the best general combiners for yield improvement. This observation supports earlier reports by Binodh et al. (2009) and Kumar (2014), who also identified these lines as superior combiners for seed yield. Overall, these findings provide a clear indication of the potential of these parental lines for sunflower breeding programs, aimed at improving key agronomic traits

Table 3 : Classification of parents with respect to general combining ability (GCA) effects for nine characters in sunflower

Parents	Days to 50% flowering	Days to maturity	Plant height(cm)	Head diameter (cm)	Seed filling (%)	100-Seed weight (g)	Volume weight (g/100ml)	Hull content (%)	Oil content (%)	Seed yield / plant (g)
lines										
CMS 248 A	P	P	P	P	P	P	G	P	P	P
CMS 243A	P	P	P	P	P	G	G	G	G	P
CMS-903A	P	A	A	P	G	A	A	G	G	P
CMS-112A	G	G	P	G	G	P	P	G	G	P
CMS-103A	G	A	G	A	G	G	P	P	P	G
CMS-10A	P	P	A	G	G	A	P	P	P	G
Testers										
EC-75717	P	P	G	P	P	P	A	P	P	G
EC-502036	P	P	P	G	P	G	G	P	P	G
EC-279309-1	P	P	G	A	P	G	P	G	G	G
J/6	P	A	G	A	P	A	P	P	P	P
IR-1-1	A	A	A	A	G	P	P	A	G	P
RHA-1-1	P	P	P	P	P	P	P	P	P	P
MRHA-2-8	G	G	A	P	G	P	G	P	P	P
R-271-1	G	A	P	G	G	G	A	G	G	G
TSG-298R	G	A	P	P	G	P	G	G	G	P

G = Good general combiner having significant GCA effects in desired direction.

A = Average general combiner having either positive or negative but non-significant GCA effects.

P = Poor general combiner having significant GCA effects in opposite direction.

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Table 4: Parents with significant or desirable GCA effects for different characters.

Characters	Lines	GCA value	Testers	GCA value
Days to 50% flowering	CMS-112A	-1.148**	MRHA-2-8	-3.787**
	CMS-103A	-1.981**	R-271-1	-0.787**
	--		TSG-298R	-1.204**
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Days to maturity	CMS-112 A	-0.574**	MRHA-2-8	-0.769**
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Plant height (cm)	CMS-103 A	-15.978**	EC-75717	-13.723**
	--	--	J/6	-11.157**
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Head diameter (cm)	CMS-112 A	0.526*	EC-502036	1.151**
	CMS-10 A	0.860**	R-271-1	1.651**
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Seed filling (%)	CMS-903A	3.058**	IR-1-1	4.869**
	CMS-112A	2.098**	MRHA-2-8	11.538**
	CMS-103A	2.782**	R-271-1	8.835**
	CMS-10A	8.741**	TSG-298R	6.157**
100 seed weight (g)	CMS-243 A	0.234**	EC-502036	0.154**
	CMS-103 A	0.202**	EC-279309-1	0.212**
	--	--	R-271-1	0.602**
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Volume weight (g/100ml)	CMS-248 A	1.731**	EC-502036	0.648*
	CMS-243 A	1.954**	MRHA-2-8	1.898**
	--	--	TSG-298R	1.565**
	--	--	--	--
Hull content (%)	CMS-243 A	-0.788**	EC-271909-1	-0.423*
	CMS-903 A	-0.300*	R-271-1	-0.775**
	CMS-112 A	-0.290*	TSG-298R	-2.007**
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Oil content (%)	CMS-243 A	1.805**	EC-271909-1	1.055**
	CMS-903 A	0.499**	IR-1-1	0.763**
	CMS-112 A	0.599**	R-271-1	1.305**
	--	--	TSG-298R	4.313**
Seed yield/ plant (g)	CMS-103 A	5.858**	EC-75717	4.453**
	CMS-10 A	5.431**	EC-502036	9.318**
	--	--	EC-279309-1	1.838*
	--	--	R-271-1	7.448**

3.4 Specific Combining Ability

Table 5 outlines the specific combining ability (SCA) effects for ten sunflower traits. Negative SCA effects are desirable for days to 50% flowering, days to maturity, plant height, and hull content, while positive effects are preferred for other traits.

Significant negative SCA effects for days to 50% flowering were observed in the crosses CMS 243 A × IR-1-1 (-3.852), CMS 248 A × MRHA-2-8 (-3.269), CMS-112 A × EC-75717 (-2.185), CMS-103 A × EC-502036 (-2.185), CMS-112 A × RHA-1-1 (-2.102), CMS-103 A × EC-75717 (-1.852), and CMS-103 A × RHA-1-1 (-1.769). These crosses are promising for reducing the days to flowering. On the positive side, the crosses CMS-103 A × MRHA-2-8 (3.731), CMS-103 A × TSG-298R (2.648), CMS 248 A × EC-75717 (2.648), CMS 243 A × EC-279309-1 (2.231), and CMS-10 A × IR-1-1 (1.815*) showed significant positive SCA effects, indicating their potential for delayed flowering.

For days to maturity, negative SCA effects were reported in the crosses CMS-103 A × IR-1-1 (-1.731), CMS 248 A × RHA-1-1 (-1.231*), CMS-103 A × EC-502036 (-0.981), CMS-10 A × J/6 (-0.926), CMS 248 A × EC-279309-1 (-0.898), and CMS 248 A × MRHA-2-8 (-0.898), highlighting their potential for early maturity. On the other hand, CMS-103 A × MRHA-2-8 (1.435) and CMS-903 A × EC-279309-1 (1.380) exhibited significant positive SCA effects, promoting longer maturity periods.

In the case of plant height, although no crosses showed significant negative SCA effects, the most desirable reductions were observed in CMS 243 A × TSG-298R (-9.642), CMS-10 A × EC-75717 (-9.004), CMS 248 A × EC-502036 (-7.777), CMS 243 A × EC-75717 (-5.299), and CMS-103 A × IR-1-1 (-4.781), indicating these crosses' potential for developing shorter plants.

For head diameter, significant positive SCA effects were recorded in CMS-112 A × R-271-1 (14.099**), CMS-112 A × TSG-298R (1.674*), and CMS-103 A × EC-75717 (1.553*), suggesting their suitability for increasing head diameter. However, negative SCA effects were observed in CMS-10 A × EC-75717 (-3.364**), CMS-903 A × R-271-1 (-2.485**), and CMS-112 A × EC-279309-1 (-2.001**).

When it came to seed filling percentage, 21 crosses showed significant positive SCA effects, with the highest being CMS-903 A × TSG-298R (14.438), followed by CMS-10 A × R-271-1 (10.676), CMS-103 A × EC-75717 (9.934), CMS 248 A × RHA-1-1 (9.256), CMS-112 A × R-271-1 (7.645), CMS 243 A × MRHA-2-8 (6.975), and CMS-103 A × EC-502036 (6.737). In contrast, significant negative SCA effects were recorded in CMS-112 A × MRHA-2-8 (-13.251), CMS-103 A × MRHA-2-8 (-10.38), CMS 248 A × R-271-1 (-10.272), and CMS-903 A × EC-502036 (-9.44), indicating reduced seed filling in these crosses.
Fourteen hybrids showed significant positive SCA effects, including CMS 248 A × RHA-1-1, CMS 243 A × R-271-1, CMS-903 A × J/6, CMS-103 A × TSG-298R, and CMS-103 A × EC-502036. Negative effects were observed in CMS-103 A × RHA-1-1 (-1.435**), CMS-10 A × R-271-1 (-0.824**), CMS 248 A × J/6 (-0.801**), and CMS-903 A × TSG-298R (-0.697**).

For volume weight (g/100ml), significant positive SCA effects were recorded in the crosses CMS 248 A × MRHA-2-8 (5.602**), CMS-112 A × J/6 (5.213), and CMS-103 A × R-271-1 (3.657), indicating their potential for improving this trait. However, negative SCA effects were observed in CMS-103 A × RHA-1-1 (-5.176), CMS-112 A × MRHA-2-8 (-4.787), CMS 248 A × J/6 (-4.398), and CMS-112 A × TSG-298R (-3.454), suggesting a reduction in volume weight.

Table 5 a: Specific combining ability effects of hybrids for character days to 50 percent flowering, days to maturity, plant height, head diameter and seed filling per cent.

Sr. No.	Characters	Days to 50 per cent Flowering	Days to Maturity	Plant height (cm)	Head diameter (cm)	Seed filling (%)
1	CMS 248 A × EC- 75717	2.648 **	0.935	2.423	1.326	-3.574 **
2	CMS 248 A × EC-502036	1.315	-0.315	-7.777	-0.371	3.444 **
3	CMS 248 A × EC-279309-1	-0.935	-0.898	-0.693	0.979	-1.663
4	CMS 248 A × J/6	1.148	0.685	2.557	0.721	1.373
5	CMS 248 A × IR-1-1	0.981	1.102	4.215	-0.321	2.486 *
6	CMS 248 A × RHA-1-1	-0.269	-1.231 *	-1.21	0.279	9.256 **
7	CMS 248 A × MRHA-2-8	-3.269 **	-0.898	-1.477	-0.696	5.322 **
8	CMS 248 A × R-271-1	-0.269	0.769	1.882	-1.321	-10.272 **
9	CMS 248 A × TSG-298R	-1.352	-0.148	0.08	-0.596	-6.374 **
10	CMS 243 A × EC-75717	1.315	0.602	-5.299	0.68	-5.756 **
11	CMS 243 A × EC-502036	-0.019	0.852	10.001	0.36	-1.809
12	CMS 243 A × EC-279309-1	2.231 **	0.769	1.584	-0.24	-4.445 **
13	CMS 243 A × J/6	1.315	-0.648	-2.266	-0.899	-5.560 **
14	CMS 243 A × IR-1-1	-3.852 **	-1.731 **	2.093	0.11	4.874 **
15	CMS 243 A × RHA-1-1	0.898	0.935	3.168	0.86	2.683 *
16	CMS 243 A × MRHA-2-8	-0.602	-0.231	-0.299	0.335	6.975 **
17	CMS 243 A × R-271-1	-0.602	-0.565	0.659	0.01	1.62
18	CMS 243 A × TSG-298R	-0.685	0.019	-9.642	-1.215	1.419
19	CMS-903 A × EC- 75717	0.593	0.213	2.123	1.486	1.173
20	CMS-903 A × EC-502036	-0.741	-0.537	-0.777	0.115	-9.440 **
21	CMS-903 A × EC-279309-1	0.009	1.380 *	-0.793	0.565	2.628 *
22	CMS-903 A × J/6	-0.407	-0.037	-4.643	0.907	1.494
23	CMS-903 A × IR-1-1	-0.074	-0.12	-3.585	-0.285	-1.827
24	CMS-903 A × RHA-1-1	1.676 *	0.046	3.99	0.165	-7.263 **
25	CMS-903 A × MRHA-2-8	-1.324	-0.62	2.123	0.24	6.713 **
26	CMS-903 A × R-271-1	1.176	0.046	-2.918	-2.485 **	-7.916 **
27	CMS-903 A × TSG-298R	-0.907	-0.37	4.48	-0.71	14.438 **
28	CMS-112 A × EC-75717	-2.185 **	-0.843	-2.071	-1.681 *	2.193 *
29	CMS-112 A × EC-502036	0.981	0.407	2.129	-1.551 *	1.266
30	CMS-112 A × EC-279309-1	0.731	-0.176	0.012	-2.001 **	2.799 **

Sr. No.	Characters	Days to 50 per cent Flowering	Days to Maturity	Plant height (cm)	Head diameter (cm)	Seed filling (%)
31	CMS-112 × J/6	-0.185	0.907	-0.838	-0.46	5.940 **
32	CMS-112 × IR-1-1	1.648 *	0.324	-0.329	-0.151	-2.852 **
33	CMS-112 A× RHA-1-1	-2.102 **	0.491	-4.004	-0.451	-5.493 **
34	CMS-112 A × MRHA-2-8	1.398	-0.176	-0.771	0.524	-13.251 **
35	CMS-112 A × R-271-1	-0.602	-0.509	1.587	4.099 **	7.645 **
36	CMS-112 A × TSG-298R	0.315	-0.426	4.286	1.674 *	1.753
37	CMS-103 A × EC-75717	-1.852 *	-0.731	11.828	1.552 *	9.934 **
38	CMS-103 A × EC-502036	-2.185 **	-0.981	-3.072	0.782	6.737 **
39	CMS-103 A × EC-279309-1	-0.435	0.435	1.011	-0.118	3.340 **
40	CMS-103 A × J/6	-0.852	0.019	-0.539	0.674	-3.419 **
41	CMS-103 A × IR-1-1	-0.519	-0.065	-4.781	0.232	-3.551 **
42	CMS-103 A × RHA-1-1	-1.769 *	-0.898	-3.906	-1.568 *	5.408 **
43	CMS-103 A × MRHA-2-8	3.731 **	1.435 *	-1.472	-0.893	-10.380 **
44	CMS-103 A × R-271-1	1.231	0.602	-1.714	-0.468	-1.754
45	CMS-103 A ×TSG-298R	2.648 **	0.185	2.644	-0.193	-6.316 **
46	CMS-10 A × EC-75717	-0.519	-0.176	-9.004	-3.364 **	-3.970 **
47	CMS-10 A × EC-502036	1.204	-0.352	-1.472	-0.893	-2.072
48	CMS-10 A × EC-279309-1	-1.713 *	-0.602	-1.714	-0.468	5.908 *
49	CMS-10 A × J/6	0.787	-0.185	2.644	-0.193	-8.812 **
50	CMS-10 A × IR-1-1	1.009	-0.741	-9.004	-3.364 **	-18.92 **
51	CMS-10 A × RHA-1-1	-0.991	-0.324	-0.504	0.665	6.102 *
52	CMS-10 A × MRHA-2-8	0.009	0.009	-1.121	0.815	-9.199 **
53	CMS-10 A × R-271-1	1.426	0.176	5.729	-0.943	2.754
54	CMS-10 A × TSG-298R	-0.074	-0.324	2.387	0.415	6.287 **
	CD 95% SCA	1.469	1.191	12.951	1.486	2.081

For hull content (%), negative SCA values, which are desirable for reducing hull content, were found in the crosses CMS-10 A × J/6 (-2.391), CMS 243 A × TSG-298R (-2.271), CMS-10 A × RHA-1-1 (-1.444), CMS 248 A × EC-502036 (-1.363), and CMS 248 A × EC-279309-1 (-1.275). Conversely, positive SCA effects were observed in CMS-103 A × RHA-1-1 (1.776), CMS-103 A × TSG-298R (1.725), CMS-10 A × EC-75717 (1.684), and CMS 248 A × J/6 (1.472).

For oil content (%), significant positive SCA effects were recorded in CMS 243 A × TSG-298R (4.487), CMS-10 A × J/6 (3.512), CMS 248 A × EC-502036 (3.023), CMS-10 A × RHA-1-1 (2.979), and CMS 248 A × EC-279309-1 (2.873), making these crosses suitable for

Table 5 b: Specific combining ability effects of hybrids for character 100 seed weight , volume weight, hull content, oil content and seed yield per plant .

Sr. No.	Characters	100 seed weight (g)	Volume weight (g/100ml)	Hull content (%)	Oil content (%)	Seed yield/ plant
1	CMS 248 A × EC- 75717	-0.134	-1.565 *	-1.197 **	0.806 *	6.558 **
2	CMS 248 A × EC-502036	0.057	-0.648	-1.363 **	3.023 **	-8.207 **
3	CMS 248 A × EC-279309-1	-0.001	-0.731	-1.276 **	2.873 **	-5.017 *
4	CMS 248 A × J/6	-0.801 **	-4.398 **	1.472 **	-3.444 **	-2.817
5	CMS 248 A × IR-1-1	-0.519 **	0.602	1.002 *	-1.835 **	-1.862
6	CMS 248 A × RHA-1-1	1.549 **	2.935 **	0.22	-0.227	4.260 *
7	CMS 248 A × MRHA-2-8	0.116	5.602 **	0.662	-1.135 **	3.103
8	CMS 248 A × R-271-1	-0.491 **	-3.231 **	0.308	0.073	0.263
9	CMS 248 A × TSG-298R	0.224	1.435	0.174	-0.135	3.718
10	CMS 243 A × EC-75717	0.149	1.213	0.533	-0.571	14.294 **
11	CMS 243 A × EC-502036	-0.559 **	-1.870 *	0.632	-1.505 **	-13.671 **
12	CMS 243 A × EC-279309-1	-0.468 **	3.546 **	0.179	-0.555	20.209 **
13	CMS 243 A × J/6	0.632 **	-2.620 **	0.852 *	-1.421 **	-6.301 **
14	CMS 243 A × IR-1-1	0.365 **	-1.12	-0.603	1.037 **	-9.396 **
15	CMS 243 A × RHA-1-1	-0.568 **	0.213	0.975 *	-2.205 **	-2.525
16	CMS 243 A × MRHA-2-8	-0.101	-2.120 **	-0.253	0.337	1.269
17	CMS 243 A × R-271-1	0.942 **	1.046	-0.043	0.395	-8.831 **
18	CMS 243 A × TSG-298R	-0.393 **	1.713 *	-2.271 **	4.487 **	4.954 *
19	CMS-903 A × EC- 75717	0.345 *	-0.954	-0.32	1.484 **	-8.949 **
20	CMS-903 A × EC-502036	0.086	-2.537 **	0.914 *	-1.749 **	5.806 **
21	CMS-903 A × EC-279309-1	0.178	1.38	0.016	0.101	2.726
22	CMS-903 A × J/6	0.728 **	-0.787	-0.371	1.384 **	3.276
23	CMS-903 A × IR-1-1	0.06	2.713 **	0.399	-0.707	-0.479
24	CMS-903 A × RHA-1-1	-0.372 **	1.546 *	-0.71	1.601 **	0.453
25	CMS-903 A × MRHA-2-8	-0.205	2.713 **	0.193	-0.257	-6.854 **
26	CMS-903 A × R-271-1	-0.122	-2.620 **	-0.471	-1.249 **	-5.524 *
27	CMS-903 A × TSG-298R	-0.697 **	-1.454	0.351	-0.607	9.541 **
28	CMS-112 A × EC-75717	-0.123	-3.454 **	-0.09	-0.766	-3.854
29	CMS-112 A × EC-502036	-0.282 *	2.963 **	-0.626	1.301 **	-2.779
30	CMS-112 A × EC-279309-1	-0.19	1.38	0.426	-0.899 *	-3.219

Sr. No.	Characters	100 seed weight (g)	Volume weight (g/100ml)	Hull content (%)	Oil content (%)	Seed yield/ plant
31	CMS-112 × J/6	0.460 **	5.213 **	0.605	-0.716	-4.649 *
32	CMS-112 × IR-1-1	0.093	0.213	-0.571	1.193 **	1.856
33	CMS-112 A× RHA-1-1	0.26	1.546 *	-0.818	1.701 **	5.998 **
34	CMS-112 A × MRHA-2-8	-0.573 **	-4.787 **	0.728	-1.507 **	3.581
35	CMS-112 A × R-271-1	0.370 **	0.38	0.554	-0.749	1.401
36	CMS-112 A × TSG-298R	-0.015	-3.454 **	-0.209	0.443	1.666
37	CMS-103 A × EC-75717	-0.218	2.824 **	-0.608	1.784 **	10.447 **
38	CMS-103 A × EC-502036	0.573 **	2.241 **	-0.387	0.601	9.212 **
39	CMS-103 A × EC-279309-1	0.415 **	-2.343 **	-0.517	0.851 *	-4.758 *
40	CMS-103 A × J/6	-0.335 *	-0.009	-0.167	0.684	3.382
41	CMS-103 A × IR-1-1	-0.197	-1.509	-0.009	-0.157	6.527 **
42	CMS-103 A × RHA-1-1	-1.435 **	-5.176 **	1.776 **	-3.849 **	-14.781 **
43	CMS-103 A × MRHA-2-8	0.482 **	-0.509	-0.942 *	1.743 **	-5.548 *
44	CMS-103 A × R-271-1	0.125	3.657 **	-0.872 *	2.101 **	4.482 *
45	CMS-103 A ×TSG-298R	0.590 **	0.824	1.725 **	-3.757 **	-8.963 **
46	CMS-10 A × EC-75717	-0.018	1.935 *	1.683 **	-2.738 **	-18.496 **
47	CMS-10 A × EC-502036	0.482 **	-0.509	-0.942 *	1.743 **	-5.548 *
48	CMS-10 A × EC-279309-1	0.125	3.657 **	-0.872 *	2.101 **	4.482 *
49	CMS-10 A × J/6	0.590 **	0.824	1.725 **	-3.757 **	-8.96 **
50	CMS-10 A × IR-1-1	-0.018	1.935 *	1.684 **	-2.738 **	-18.50**
51	CMS-10 A × RHA-1-1	0.124	-0.148	0.829	-1.671 **	9.639 **
52	CMS-10 A × MRHA-2-8	0.066	-3.231 **	1.171 **	-2.371 **	-9.94 **
53	CMS-10 A × R-271-1	-0.684 **	2.602 **	-2.391 **	3.512 **	7.109 **
54	CMS-10 A × TSG-298R	0.198	-0.898	-0.217	0.47	3.354
	CD 95% SCA	0.271	1.513	0.846	0.77	4.222

improving oil content. Negative SCA effects were observed in CMS-103 A × RHA-1-1 (-3.849), CMS-103 A × TSG-298R (-3.757), CMS 248 A × J/6 (-3.444), CMS-10 A × EC-75717 (-2.738), and CMS-10 A × EC-279309-1 (-2.371).

In terms of seed yield per plant (g), the crosses CMS 243 A × EC-279309-1 (20.209**), CMS 243 A × EC-75717 (14.294**), CMS-103 A × EC-75717 (10.447**), CMS-10 A × EC-502036 (9.639**), and CMS-903 A × TSG-298R (9.541) exhibited significant positive SCA effects, highlighting their potential for yield improvement. In contrast, negative SCA effects were noted in CMS-10 A × EC-75717 (-18.496**), CMS-103 A × RHA-1-1 (-14.781**), CMS 243 A × EC-502036 (-13.671**), CMS-10 A × TSG-298R (-10.916**) and CMS-10 A × EC-279309-1 (-9.941**), indicating reduced seed yield potential in these combinations.

Specific combining ability (SCA) refers to the deviation in performance of hybrid combinations from what would be expected based on the average performance of their parents. In the present investigation, the hybrids with significant and desirable SCA effects are presented in Table 5 . Additionally, Tables 5 a and 5 b categorize hybrids based on desirable SCA values in a favorable direction, along with the general combining ability (GCA) effects of the involved parents. Negative SCA effects were desirable for traits like days to 50 per cent flowering, days to maturity, plant height, and hull content in sunflower.

Among the 54 crosses analyzed, five crosses exhibited significant SCA effects in the desired direction for days to 50 per cent flowering, three for days to maturity, none for plant height, and eight for hull content. Furthermore, three crosses showed significant SCA effects for head diameter, one cross for seed filling, twelve for 100-seed weight, eleven for volume weight, fifteen for oil content, and thirteen for seed yield per plant. These results indicate that crosses with significantly negative SCA effects for traits such as days to flowering, maturity, and plant height contribute favorable additive genes for earliness and shorter plant height, as reported by Kulkarni and Supriya (2017).

For days to 50% flowering, the crosses CMS 243 A × IR-1-1, CMS 248 A × MRHA-2-8, and CMS-112 A × EC-75717 demonstrated significant positive SCA effects. The parental GCA effects were classified as low × high, low × high, and high × low, respectively. In terms of days to maturity, the hybrids CMS 243 A × IR-1-1, CMS-10 A × EC-279309-1, and CMS 248 A × RHA-1-1 displayed desirable SCA effects with low × high, low × low, and low × low GCA statuses. Significant SCA effects for plant height were observed in CMS 248 A × EC-502036, CMS-10 A × EC-75717, and CMS 243 A × TSG-298R, regardless of parental GCA status (low × low, high × high, and low × low, respectively).

For head diameter, the crosses CMS-112 A × R-271-1, CMS-112 A × TSG-298R, and CMS-103 A × EC-75717 exhibited significant SCA effects, with parental GCA statuses of high × high, high × low, and high × low. Similarly, significant SCA effects for seed filling were found in CMS 248 A × R-271-1, CMS-103 A × MRHA-2-8, and CMS-112 A × MRHA-2-8, driven by low × high, high × high, and high × high GCA effects. For 100-seed weight, the crosses CMS 248 A × RHA-1-1, CMS 243 A × R-271-1, and CMS-903 A × J/6 showed significant SCA effects, with GCA patterns of low × low and high × high.

Volume weight was positively influenced by SCA effects in the crosses CMS 248 A × MRHA-2-8, CMS-112 A × J/6, and CMS-103 A × R-271-1, which involved high × high, low × low, and low × high GCA effects. Significant SCA effects for hull content were reported in CMS-10 A × J/6, CMS 243 A × TSG-298R, and CMS-10 A × RHA-1-1, with parental GCA statuses of low × low, high × high, and low × low, respectively.

For oil content, the crosses CMS 243 A × TSG-298R, CMS-10 A × J/6, and CMS 248 A × EC-502036 exhibited beneficial SCA effects, with parental GCA patterns of high × high and low × low. Finally, seed yield per plant was significantly affected by SCA in the crosses CMS 243 A × EC-279309-1, CMS 243 A × EC-75717, and CMS-103 A × EC-75717, irrespective of parental GCA status.

These findings are consistent with prior research. Positive SCA values for seed yield and contributing traits were reported by Shekhar et al. (2000), Borde et al. (2017), and Singh and Kumar (2018). Darvishzadeh et al. (2014) and Hldani et al. (2014) highlighted significant SCA effects for head diameter, while Shinde et al. (2016) and Ingle et al. (2017) reported the same for volume weight. Kaya (2005) demonstrated SCA effects for hull content, and Salim and Ali (2012) emphasized positive SCA for oil content. Turec and Goksoy (2006) underscored the influence of parental combining abilities on the heterotic performance of hybrids, with superior hybrids resulting from parents with high GCA and SCA .

Among the top-ranked specific combiners for seed yield per plant, CMS 243 A × EC-279309-1, CMS 243 A × EC-75717, and CMS-103 A × EC-75717 were noted for their significant SCA effects across key traits such as head diameter, seed filling, 100-seed weight, volume weight, and hull content. This aligns with earlier reports by Rukminidevi et al. (2005).

Based on heterosis studies and considering the best-performing hybrids over the best standard check, per se performance, GCA, and SCA effects , the hybrids CMS-103 A × EC-502036, CMS-10 A × EC-502036, CMS 243 A × EC-279309-1, CMS-10 A × R-271-1, and CMS-103 A × EC-75717 were identified as superior heterotic hybrids for seed yield per plant. These hybrids also demonstrated desirable heterosis and SCA effects for traits such as head diameter, seed filling, volume weight, 100-seed weight, oil content, days to flowering, and days to maturity.

The involvement of parents with high × high GCA suggests the presence of additive gene action, making these hybrids suitable for selection, while low × high GCA indicates non-additive gene action, supporting their use in heterosis breeding programs. These findings align with the conclusions of Sujatha and Reddy (2009).

4. CONCLUSION

The analysis revealed significant GCA effects for most traits, indicating the importance of additive gene action. Lines CMS-112A, CMS-103A, and CMS-243A showed superior GCA for multiple traits, including earliness, head diameter, seed filling, hull content, volume weight, and oil content. Among testers, EC-502036, R-271-1, and TSG-298R were identified as excellent general combiners for traits like seed yield, head diameter, and oil conte

Significant SCA effects were observed for most traits, indicating the importance of non-additive gene action. The hybrids CMS-103A × EC-502036, CMS-10A × EC-502036, CMS-243A × EC-279309-1, and CMS-10A × R-271-1 exhibited high SCA effects for seed yield and related traits, such as head diameter and seed filling, surpassing the best check. CMS-243A × TSG-298R and CMS-112A × TSG-298R showed the highest SCA for oil content.

The ratio of GCA to SCA was less than unity for most traits, suggesting that non-additive gene action predominates, which can be exploited through heterosis breeding. For days to 50% flowering and seed filling, additive gene action was more significant, indicating the potential for pedigree breeding to improve inbreds in these traits.

The study identified CMS-112A, CMS-103A, CMS-243A, and CMS-10A as promising lines, and testers EC-502036, R-271-1, and TSG-298R as good combiners for yield and related traits. The hybrids CMS-103A × EC-502036 and CMS-10A × EC-502036 are recommended for commercial exploitation, with further multi-location testing to assess stability and performance across diverse environments.

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