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Combining Ability Analysis for Yield and Associated Traits in Sunflower (*Helianthus annuus* L.) F_1 Hybrids under Normal and Heat Stress Conditions

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Abstract

Heat stress is one of the highest environmental restraints limiting sunflower productivity worldwide by adversely affecting flowering, seed development, and oil accumulation. The present study was conducted to estimate the general combining ability (GCA) and specific combining ability (SCA) of sunflower parental lines and their F_1 hybrids under normal and heat stress environments using the Line × Tester mating design. Analysis of variance revealed highly significant differences among genotypes, parents, crosses, and line × tester interactions for most of the traits studied, indicating the presence of substantial genetic variability. Significant GCA and SCA variances suggested that both additive and non-additive gene effects contributed to the inheritance of the evaluated characters, although the magnitude of SCA variance was comparatively higher for several economically important traits, demonstrating the predominance of non-additive gene action. Several parental lines exhibited desirable GCA effects for seed yield and related traits, whereas several cross combinations expressed high positive SCA effects under both normal and heat stress conditions, indicating their potential for hybrid development. Heat stress considerably reduced the overall performance of most genotypes; however, selected hybrids maintained comparatively superior performance, suggesting improved adaptation to elevated temperature. The findings provide valuable information for sunflower breeding strategies targeting improved productivity and heat stress tolerance under changing climatic conditions.

Keywords: Sunflower; combining ability; line × tester analysis; heat stress; seed yield, Oil content.

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Introduction

Sunflower (*Helianthus annuus* L.) is one of the most important oilseeds crops worldwide and is widely cultivated for its high-quality edible oil (Mmbando & Massawe, 2025). Global demand for vegetable oils has increased rapidly over the past few decades due to population growth. Besides its significance as a source of premium vegetable oil, sunflower also contributes substantially to livestock feed through its protein-rich meal and serves as a valuable raw material for the food, pharmaceutical, and biofuel industries. (OECD/FAO, 2026; Muhammad et al., 2026). However, achieving higher and stable seed yield remains challenging because crop productivity is strongly influenced by environmental stresses, particularly high temperatures during the reproductive stage (Dunareanu et al., 2025). Heat stress adversely affects almost every developmental stage of sunflower growth. Elevated temperatures reduce pollen viability, impair fertilization, shorten the grain-filling period, and accelerate leaf senescence, ultimately resulting in reduced seed number, lower seed weight, and diminished oil accumulation. These physiological and biochemical disturbances collectively reduce both seed yield and oil quality. (Rahnama et al., 2026, Mehmood et al., 2025). Combining ability analysis provides valuable information regarding genetic architecture controlling quantitative traits and assists breeders in selecting superior parents and cross combinations. The concept of combining ability, proposed by Sprague and Tatum (1942), partitions genetic variation into general combining ability (GCA) and specific combining ability (SCA). Among various mating designs, the Line × Tester analysis developed by Kempthorne (1957) has been extensively used to estimate GCA and SCA effects in self- and cross-pollinated crops. This mating design enables simultaneous evaluation of parental lines and their hybrids while providing reliable estimates of additive and non-additive genetic variances. Numerous studies have successfully employed Line × Tester analysis in sunflowers to investigate the inheritance of seed yield, flowering behavior, plant architecture, head diameter, thousand-seed weight, oil content, and several physiological traits associated with stress tolerance (Singh et al., 2025). In view of these considerations, the present investigation was undertaken to estimate the general combining ability (GCA) and specific combining ability (SCA) of selected sunflower parental lines and their F_1 hybrids using the Line × Tester mating design under normal and heat stress conditions.

Materials and Methods

The current research was conducted to assess heat resistance on genetically basis for sunflower (*Helianthus annuus* L.) genotypes. In this regard eight potential heat resistance genotypes crossed in Line x Tester (5 x 3) (five lines: Hysun-39, PSF-025, TJ-1, Peshawar-93, Parsan-3 and three testers: HO-1, Thatta, A-1) mating design to produce F_1 hybrids for combining ability analysis. Then the fifteen f1 hybrids of sunflower and their eight respective parents were grown in the experimental field of Oilseeds Research Institute Tandojam in spring season 2019, the design was randomized complete block design having three replications and two treatments, to evaluate the genetic performance of parental lines and their hybrids under normal and heat stress conditions, T1 Normal: Normal sowing date, T2 Heat stress: Late sowing date. These ten traits (Days to 50% flowering, Days to 90% maturity, Plant height (cm), Head diameter (cm), 100-seed weight (g), Number of seeds head^{-1}, Grain yield plot^{-1} (Kg), Oil

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content (%)) were recorded on randomly selected competitive plants from each experimental unit using standard procedures. All recommended agronomic and crop management practices were followed uniformly throughout the experimental period.

Statistical Analysis

The recorded data from both normal and heat stress environments for analysis of variance (ANOVA) was done according to Gomez and Gomez (1984). General combining ability (GCA) effects of parental lines and testers and specific combining ability (SCA) effects of F_1 hybrids were estimated according to the method proposed by Kempthorne (1957).

The analysis partitioned the total genetic variation into additive and non-additive genetic components to determine the relative contribution of each type of gene action in the inheritance of the studied traits. The relative importance of additive and non-additive gene action was assessed by comparing GCA and SCA variance components using the following formula.

Estimation of GCA effects

(a) Lines

$$g_i = \frac{\times i..}{tr} - \frac{\times ...}{ltr}$$

(b) Testers:

$$g_i = \frac{\times .j.}{lr} - \frac{\times ...}{ltr}$$

Where;

L = number of CMS lines (female parents)
T = number of testers (male parents)
R = number of replications
×i. = Total of the F_1s resulting from crossing with lines to all the testers
×.j. = Total of all crosses of tester with all the lines
×… = Total of all the crosses

Estimation of SCA effects

$$Sij = \frac{\times ij}{r} - \frac{\times i..}{tr} - \frac{\times .j.}{lr} + \frac{\times ...}{ltr}$$

Where;

×**ij** = Total of F_1s resulting from crossing line with tester.p
All statistical analyses were performed using appropriate statistical software, and ms office 2016.

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Results and Discussion

Analysis of Variance and Combining Ability

Combining ability analysis is one of the most effective approaches for identifying superior parental lines and promising hybrid combinations, while also determining the relative importance of additive and non-additive gene effects governing quantitative traits. The line × tester mating design has been widely employed in crop improvement programmes to estimate general combining ability (GCA) and specific combining ability (SCA), thereby facilitating the selection of elite parents for hybrid development (Sabaghnia et al., 2010). Similar approaches have been successfully applied in wheat, cotton, maize, rice, rapeseed, and sunflower breeding programmes (Bilwal et al., 2018; Sheikh et al., 2021; Siahbidi et al., 2022). The analysis of variance (ANOVA) revealed highly significant ($p \leq 0.05$) differences among sunflower genotypes for all studied traits, including days to 50% flowering, days to 90% maturity, plant height, head diameter, 100-seed weight, number of seeds head^{-1}, grain yield plot^{-1}, stem girth, oil content, and protein content under both non-stress and heat-stress environments (Table 01). These significant differences indicate the presence of substantial genetic variability among the parental lines and hybrids, providing considerable scope for genetic improvement through selection and hybrid breeding. Similarly, the analysis of combining ability showed significant mean squares for both GCA and SCA across the majority of the investigated traits under both environments (Table 02), indicating that both additive and non-additive gene effects contributed to trait inheritance. However, GCA mean squares were generally greater than SCA for most traits, suggesting the predominance of additive gene action. The parental lines HO-1, TJ-1, and Peshawar-93 were identified as superior general combiners, whereas the hybrids Hysun-39 × HO-1, Parsan-3 × HO-1, and Peshawar-93 × Thatta exhibited superior SCA effects, demonstrating their potential for developing high-yielding and heat-tolerant sunflower hybrids. The present findings agree with previous reports of (Bavage et al., 2021), Ashraf et al. (2024), Gund et al. (2024), Singh et al., (2025) and Krishna Sri et al. (2026), who also reported significant GCA and SCA effects for yield and related traits in sunflower.

Table 01: Mean squares of various traits of sunflower genotypes in F_1 generation

SOV	Replication	Genotypes	Treatments	G × T	Parents	F_1 hybrids	P vs. C	Errors
Degrees of Freedom	**2**	**22**	**1**	**22**	**7**	**14**	**1**	**90**
Characters								
Days to 75% flowering	0.92	257.56**	4454.03**	49.89**	52.16**	76.11**	4235.49**	18.61

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Days to 90% maturity	65.74	361.64**	250.69**	216.16**	266.65**	159.16**	3861.23**	24.18
Plant height (cm)	290.9	767.50**	32169.9*	373.8**	5.43*	303.9*	12591.42**	106.1
Head Diameter (cm)	7185.22	238.19 ^{ns}	9122.35**	148.80 ^{ns}	4.66 ^{ns}	2.62 ^{ns}	5171.07**	335.47
100 seed weight (g)	1.82	0.94*	6.18**	0.97*	288954**	09714**	2022673**	0.49
Number of seed head^{-1}	39481	176082**	2679101**	66967**	109.52	58388**	3055596**	15277
Grain yield plot^{-1} (Kg)	0.62	0.49**	0.95**	0.06^{ns}	0.19^{ns}	0.34*	4.58**	0.15
Oil content (%)	0.22	27.65**	190.40**	5.58**	17.99**	7.36**	379.28**	2.083

**,*significant level at 1 and 5% of probably levels, respectively, while, ns indicates non-significant

Table 02 Mean squares of GCA and SCA of F_1 sunflower

Source of variance	Non-Stress				Heat Stress			
	GCA		SCA	Error	GCA		SCA	Error
	Lines	Tester	Lines × Tester	(D.F.40)	Lines	Tester	Lines × Tester	(D.F.40)
	(D.F.7)		(D.F.15)		(D.F.7)		(D.F.15)	
Days to 75% flowering	146.39**	23.89^{ns}	56.51**	14.32	67.50**	21.67**	30.00**	6.73
Days to 90% maturity	358.37**	55.76*	125.57**	22.94	109.52**	60.69**	50.12*	21.19
Plant height (cm)	1260.3**	86.49**	415.55**	12.90	36.81*	66.20**	55.10*	20.94
Head Diameter (cm)	6.56**	0.77^{ns}	2.40**	0.63	1.69**	0.12^{ns}	0.67^{ns}	0.72
100 seed weight (g)	2.53**	0.15^{ns}	1.03**	0.17	0.30*	0.27*	0.20^{ns}	0.13
Number of seed head^{-1}	105236.1**	14682.2^{ns}	56750.79*	15262.9	36941.1**	19535.56^{ns}	20854.60*	12109.84
Grain yield plot^{-1} (Kg)	0.46**	0.07^{ns}	0.20^{ns}	0.14	0.44**	0.02^{ns}	0.16^{ns}	0.11
Oil content (%)	0.14^{ns}	0.01^{ns}	9.15**	1.22	0.10^{ns}	0.00^{ns}	2.13*	1.35

**,*significant level at 1 and 5% of probably levels respectively, while ns showed non-significant

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Combining ability effects
Earliness Traits (days to 75% Flowering and 90% maturity)

Early flowering and early maturity are a desirable breeding objective in major oilseeds crops, especially in sunflowers, because early flowering and early maturing genotypes enable plants to escape heat stress, complete reproductive development and their life cycle before the start of severe environmental conditions. Days to 75% flowering and days to 90% maturity exhibited significant variation among the parental lines and F_1 hybrids under both non-stress and heat-stress conditions, indicating the presence of substantial genetic variability for flowering behavior. The superior general combining ability (GCA) effects for days to 75% flowering revealed by parents TJ-1 and PSF-025 (−4.00 and −3.00), whereas days to 90% maturity effects exhibited by HO-1 and Hysun-39 (-10.27 and -5.47) as the best general combiners, under non-stress and heat-stress conditions, suggest that these parents possess favorable additive alleles for earliness and can therefore be effectively utilized in future hybridization programmes. Similarly, superior specific combining ability (SCA) effects for flowering expressed by Peshawar-93 × HO-1 (−3.11) and Parsan-3 × A-1 (−2.33), nevertheless the SCA effects for days to 90% maturity displayed by PSF-025 × A-1 (−3.62) and Parsan-3 × A-1 (−2.87) F_1 hybrids, under non-stress and under heat stress conditions which is the best hybrid combinations for early flowering and demonstrates the importance of non-additive gene action. These results indicate that both additive and non-additive genetic effects contributed to the inheritance of flowering time. Similar findings have been reported by Akbar et al. (2008), Sabaghnia et al. (2010), Zareei Siahbidi et al. (2022), Singh et al. (2025), and Krishna Sri et al. (2026), who also observed significant GCA and SCA effects for flowering-related traits in sunflower, indicating the involvement of both additive and dominance gene actions in the inheritance of earliness (Table 03 and 04).

Plant Growth Traits (Plant Height)

Plant height is important agronomic trait that influences plant vigor, lodging resistance, biomass production, and ultimately seed yield in sunflower. An optimum plant height contributes to better adaptation under heat-stress conditions. The trait plant height is important selection criteria in sunflower breeding programmes (Akbar et al., 2008; Reddy et al., 2017). The analysis of combining ability revealed significant genetic variation for plant height under non-stress and heat-stress environments (Tables 03 and 04). For plant height, the parental line TJ-1 exhibited the highest positive GCA effects (10.80 under non-stress and 3.04 under heat stress), indicating the presence of favorable additive alleles for plant vigor. Likewise, the hybrids TJ-1 × HO-1 (5.78) and PSF-025 × Thatta (4.84) recorded the highest SCA effects under non-stress and heat-stress conditions. The significant GCA and SCA effects for plant height indicate that both additive and non-additive gene actions contribute to the inheritance of these traits. These parents can be effectively utilized in breeding programmes aimed at improving plant architecture and heat tolerance. The present findings are in agreement with those of Reddy et al. (2017), Bilwal et al. (2018), Vairam and Gnanamalar (2023), Singh et al. (2025), and Krishna Sri et al. (2026), who also reported significant GCA and SCA effects for

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plant growth, confirming the involvement of both additive and non-additive gene actions in sunflower.

Yield-Contributing Traits (Head Diameter and Number of Seeds Head^{-1})

Yield contributing traits play very important role in yield production, like head diameter and number of seeds head^{-1} are known as the most important yield parameters in sunflower because they directly influence the seed yield. A larger head diameter generally leads to increased seed set and higher grain productivity. Combining ability effects extensively utilized to determine the quantitative traits on genetic basis, to identify elite parents and hybrids possessing superior breeding value. The analysis of combining ability revealed significant genetic variation for both head diameter and number of seeds head^{-1} among the parental lines and F_1 hybrids under non-stress and heat-stress conditions given in table (Tables 03, 04 and 05, 06). For head diameter, the parental line HO-1 exhibited the highest positive general combining ability (GCA) effects (1.39 under non-stress and 0.48 under heat stress), demonstrating its superior breeding value. Likewise, the hybrid Parsan-3 × A-1 expressed the highest positive specific combining ability (SCA) effects (0.70 and 0.46) under non-stress and heat-stress conditions for enhancing head diameter. Similarly, the number of seeds head^{-1} the parental lines HO-1 (177.78) under non-stress and A-1 (86.44) under heat-stress conditions were identified as the best general combiners, indicating their ability to transmit favorable additive genes controlling seed-setting efficiency and reproductive performance. Among the hybrids, Hysun-39 × HO-1 (178.89) under non-stress and Peshawar-93 × HO-1 (119.56) under heat-stress conditions exhibited the highest positive SCA effects, reflecting superior non-additive genetic interactions. The simultaneous significance of GCA and SCA effects for both head diameter and number of seeds head^{-1} demonstrates that these yield-contributing traits are controlled by the combined action of additive and non-additive gene effects. The present findings are consistent with those reported by Akbar et al. (2008), Vairam and Gnanamalar (2023), Singh et al. (2025), Mariam et al. (2025), Krishna Sri et al. (2026) and Svitlakova et al. (2026), who likewise reported significant GCA and SCA effects for head diameter and seed number in sunflower, confirming the involvement of both additive and dominance gene actions in the inheritance of these economically important yield components.

Yield Traits (100-Seed Weight and Grain Yield Plot^{-1})

Seed index (100 seed weight in g) and grain yield per plot are the very important major parameters of sunflower which affect the sunflower productivity and economically returns, the grain yield per plot is the cumulative results of yield and yield contributing traits like including head diameter, number of seeds per head, and seed weight. Combining ability analysis provides valuable information for identifying superior parents and hybrid combinations capable of producing stable and high-yielding progenies under contrasting environmental conditions (Akbar et al., 2008; Ailwar et al., 2020; Bavage et al., 2021; Ghodekar et al., 2025). The analysis of combining ability revealed highly significant genetic variation for both 100-seed weight and grain yield plot^{-1} among the parental lines and F_1 hybrids under non-stress and heat-stress conditions (Tables 05 and 06). For 100-seed weight, the parental line TJ-1 exhibited the highest positive general combining ability (GCA) effect (0.53) under non-stress conditions,

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whereas HO-1 recorded the highest positive GCA effect (0.12) under heat-stress conditions. Likewise, among the hybrid combinations, Peshawar-93 × Thatta (0.45) and Hysun-39 × HO-1 (0.39) expressed the highest positive specific combining ability (SCA) effects under non-stress conditions. Under heat stress, Hysun-39 × HO-1 (0.22) and Parsan-3 × HO-1 (0.18) emerged as the best specific combiners, indicating the importance of favorable non-additive gene interactions in improving seed weight under elevated temperature conditions. Similarly, grain yield plot^{-1} exhibited significant GCA and SCA effects under both environments, confirming substantial genetic variability for yield performance. The parental lines HO-1 (0.23) under non-stress and A-1 (0.17) under heat-stress conditions were identified as the best general combiners for grain yield. Among the hybrid combinations, Hysun-39 × HO-1 (0.27) under non-stress and PSF-025 × A-1 (0.19) under heat-stress conditions expressed the highest positive SCA effects, demonstrating the contribution of favorable dominance and epistatic interactions. The significant GCA and SCA effects indicated the economic importance of yield traits which are governed due to additive and non-additive gene effects. This indicates that grain yield in sunflower is a complex quantitative trait resulting from the cumulative interaction of several component characters rather than the expression of a single trait alone. The present findings are in close agreement with those of Sheikh et al. (2021), Singh et al. (2025), Ahmad et al. (2025) and Krishna Sri et al. (2026), who likewise reported significant GCA and SCA effects for seed weight and grain yield, confirming the importance of both additive and non-additive gene actions in the inheritance of these traits.

Quality Trait (Oil Content)

Oil content is the major quality trait determining the nutritional and economic value of sunflowers. Since sunflowers are primarily cultivated as edible oil crops, improving oil content is major objective of breeders. Therefore, identifying superior parental lines and hybrid combinations for these traits is essential for developing high-quality and heat-tolerant sunflower cultivars (Kaya and Atakisi, 2004; Akbar et al., 2008; Reddy et al., 2017). The combining ability effects revealed significant genetic variation for oil content under non-stress and heat-stress conditions (Tables 05 and 06). For oil content, TJ-1 (1.21) under non-stress and PSF-025 (0.70) under heat-stress conditions exhibited the highest positive GCA effects, indicating their superior breeding value for improving seed oil content. Among the hybrids, Parsan-3 × A-1 (2.28) under non-stress and PSF-025 × Thatta (1.19) under heat stress expressed the highest SCA effects. However, the superior and stable GCA performance of TJ-1 and PSF-025 across contrasting environments suggests that additive gene effects play a predominant role in improving seed quality. The superior performance of specific hybrid combinations further indicates that superior breeding can be effectively utilized to enhance oil contents under heat-stress conditions. These findings are in agreement with those of Ailwar et al. (2020), Bavage et al. (2021), Sheikh et al. (2021), Singh et al. (2025), and Krishna Sri et al. (2026), who also reported significant GCA and SCA effects for seed quality traits, confirming the combined influence of additive and non-additive gene actions on oil content in sunflower.

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Table 03 General combining ability effects for various yield and oil traits of sunflower

Parents	Days to 75% flowering		Days to 90% maturity		Plant height		Head diameter (cm)	
	Control	Heat stress	Control	Heat Stress	Control	Heat Stress	Control	Heat Stress
Testers								
HO-1	6.00	4.22	-10.27	-5.47	-16.98	0.04	1.39	0.48
A-1	0.44	-0.78	1.96	-0.47	-7.53	-2.51	-0.17	-0.19
Thatta	1.00	0.89	6.29	4.09	5.36	-0.84	-0.83	-0.52
Lines								
PSF-025	-3.44	-3.00	-1.04	0.64	8.36	0.27	0.11	0.42
TJ-1	-4.00	-1.33	3.07	1.20	10.80	3.04	-0.50	-0.19
Peshawar-93	0.89	1.33	-1.49	-1.36	-2.36	-2.07	0.08	0.10
Hysun-39	0.56	-0.33	-0.69	-0.96	-0.09	-0.07	0.18	-0.03
Parsan-3	-1.44	-1.00	2.18	2.31	2.44	2.13	-0.26	-0.07
S.E of testers	0.98	0.67	1.24	1.19	0.93	1.18	0.20	0.22
S.E of lines	1.26	0.87	1.60	1.53	1.20	1.53	0.26	0.28

Table 04 Specific combining ability effects for different yield and oil traits of F_1 sunflower

F_1 hybrids	Days to 75% flowering		Days to 90% maturity		Plant height		Head diameter	
	control	Heat stress	control	Heat stress	control	Heat stress	Control	Heat stress
Hysun-39 × HO-1	1.33	-0.22	-0.73	-0.87	-5.42	-4.38	0.31	0.12
PSF-025 × HO-1	-1.67	-0.22	1.80	0.40	-0.36	0.29	-0.12	0.09
TJ-1 × HO-1	0.33	0.44	-1.07	0.47	5.78	4.09	-0.19	-0.21
Peshawar-93 × HO-1	-3.11	1.44	-2.96	-0.87	-4.87	-5.16	0.20	0.12
Parsan-3 × HO-1	0.56	-1.89	-0.42	-1.27	0.53	1.18	0.27	0.09
Hysun-39 × Thatta	2.56	0.44	3.38	2.13	4.33	3.98	-0.47	-0.21
PSF-025 × Thatta	1.33	1.44	-2.29	-2.09	1.58	4.84	0.03	-0.04
TJ-1 × Thatta	0.00	-1.89	-0.09	-0.49	-0.69	1.18	-0.40	-0.24
Peshawar-93 × Thatta	-1.33	0.44	2.38	2.58	-0.89	-6.02	0.37	0.29

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Parsan-3 × Thatta	0.78	-1.33	3.38	3.02	4.24	2.07	0.09	0.18
Hysun-39 × A-1	-2.22	0.33	0.24	-0.71	-1.36	0.07	0.32	0.14
PSF-025 × A-1	1.44	1.00	-3.62	-2.31	-2.89	-2.13	-0.41	-0.32
TJ-1 × A-1	-0.33	-1.33	2.60	0.80	4.47	2.62	-0.63	-0.38
Peshawar 93 × A-1	3.33	3.67	-1.53	2.07	1.87	-2.71	-0.07	-0.08
Parsan-3 × A-1	-3.00	-2.33	-1.07	-2.87	-6.33	0.09	0.70	0.46
S.E of SCA	2.19	1.50	2.77	2.66	2.07	2.64	0.46	0.49

Table 05 General combining ability effects for various yield and oil traits of sunflower

Parents	100 seeds weight		Number of seeds head^{-1}		Grain yield plot^{-1} (kg)		Oil content %	
	Control	Heat stress	Control	Heat stress	control	Heat stress	Control	Heat stress
Testers								
HO-1	0.47	0.12	177.78	50.89	0.23	0.14	0.12	0.14
A-1	0.02	0.08	12.78	86.44	0.07	0.17	-0.28	-0.14
Thatta	-0.73	-0.31	-96.11	-50.22	-0.21	-0.20	-2.03	-0.70
Lines								
PSF-025	-0.29	-0.03	-72.78	-48.00	-0.27	-0.28	0.98	0.70
TJ-1	0.53	0.14	-21.67	-39.11	0.18	0.17	1.21	0.00
Peshawar-93	0.08	0.14	5.56	14.89	0.03	-0.02	0.08	0.14
Hysun-39	0.03	-0.13	14.22	14.22	-0.08	-0.02	0.26	-0.10
Parsan-3	-0.11	-0.01	-19.78	-29.11	0.05	0.04	-0.34	-0.04
S.E of testers	0.11	0.09	31.90	28.41	0.10	0.09	0.28	0.30
S.E of lines	0.14	0.12	41.18	36.68	0.13	0.11	0.37	0.39

Table 06 Specific combining ability effects for different yield and oil traits of F_1 sunflower

F_1 hybrids	100-seeds weight (g)		Number of seeds head^{-1}		Grain yield plot^{-1} (kg)		Oil content %	
	control	Heat stress	control	Heat stress	control	Heat stress	Control	Heat stress
Hysun-39 × HO-1	0.39	0.22	178.89	-1.56	0.27	0.16	0.08	-0.64
PSF-025 × HO-1	0.10	-0.18	-51.44	-4.22	-0.15	-0.13	-0.18	0.10
TJ-1 × HO-1	-0.49	-0.04	-127.44	5.78	-0.12	-0.03	0.10	0.54

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Peshawar-93 × HO-1	0.16	0.08	5.56	119.56	0.11	0.04	0.48	-0.53
Parsan-3 × HO-1	0.14	0.18	6.89	-23.11	-0.02	0.15	1.62	1.04
Hysun-39 × Thatta	-0.31	-0.27	-12.44	-96.44	-0.09	-0.19	-2.10	-0.51
PSF-025 × Thatta	-0.08	-0.03	4.44	-53.78	-0.12	-0.03	1.03	1.19
TJ-1 × Thatta	-0.37	-0.09	-20.89	-3.11	0.09	0.01	-1.02	-0.57
Peshawar-93 × Thatta	0.45	0.12	16.44	56.89	0.02	0.01	-0.01	-0.62
Parsan-3 × Thatta	-0.52	-0.30	-212.22	-82.67	-0.13	-0.08	-1.18	-0.28
Hysun-39 × A-1	0.19	0.13	82.44	28.00	-0.05	-0.11	1.44	-0.80
PSF-025 × A-1	0.34	0.18	129.78	54.67	0.18	0.19	-0.26	1.08
TJ-1 × A-1	0.05	0.03	23.33	18.44	-0.14	-0.09	-0.41	0.26
Peshawar-93 × A-1	-0.07	-0.04	-17.00	2.44	0.14	0.08	-1.86	0.23
Parsan-3 × A-1	0.01	0.01	-6.33	-20.89	0.00	0.01	2.28	-0.49
S.E of SCA	0.24	0.21	71.33	63.53	0.22	0.20	0.64	0.67

Conclusion

The Line × Tester analysis revealed significant genetic variability among sunflower parents and hybrids under both non-stress and heat-stress conditions. Both additive (GCA) and non-additive (SCA) gene effects contributed to the inheritance of yield, yield-related, and quality traits. The parental lines TJ-1, HO-1, PSF-025, and A-1 were identified as promising general combiners, while hybrids such as Hysun-39 × HO-1, Parsan-3 × A-1, PSF-025 × A-1, and PSF-025 × Thatta exhibited superior specific combining ability under heat stress. These parents and hybrids can serve as valuable genetic resources for developing high-yielding, heat-tolerant, and high-oil sunflower hybrids.

Novelty Statement

This study is among the few investigations evaluating the combining ability of sunflower genotypes under both normal and heat-stress environments using the Line × Tester mating design. It identified superior parental lines and hybrid combinations with stable performance for yield and oil content under high-temperature conditions, providing valuable genetic resources for breeding climate-resilient sunflower hybrids.

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