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# Heterosis and Combining Ability via Line × Tester Analysis for Seed Yield and Yield-Contributing Traits in Safflower (*Carthamus Tinctorius* L.)

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***Authors' contributions***

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

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## Abstract

**Aims:** The experiment was conducted to study the general combining ability (GCA) of the parental lines and the specific combining ability (SCA) of the hybrids.
**Study Design:** Randomised block design
**Place and Duration of Study:** The study was conducted at the Field Experimentation Centre of the Department of Genetics and Plant Breeding, Naini Institute of Agriculture, Sam Higginbottom University of Agriculture, Technology & Sciences, Prayagraj (UP), during 2022-23 and 2023-24.
**Methodology:** Four lines and five testers raised in a crossing block were crossed using the line x tester method to produce 20 hybrids during the year. The resultant 20 hybrids, along with nine parents and the check Sharda, were evaluated in a randomised block design with three replications.
**Results:** The analysis of variance showed highly significant differences among the 30 genotypes for all the characters studied. The hybrid SSF-1870×SSF-1240 showed the highest standard heterosis for seed yield (27.95%), number of capitula (23.83%)

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and number of secondary branches (17.46%). The hybrid SSF-1870×SSF-18123 showed the maximum relative heterosis of 67.84% for seed yield. The hybrid SSF-1871×SSF-1704 showed the maximum standard heterosis for oil content (14.15%), and the highest heterosis over the mid-parent for oil content was recorded by the hybrid SSF-1870×SSF-1872 (32.89%). Combining ability analysis indicated that the mean sums of squares due to SCA were higher than those due to GCA for all the traits studied, indicating the predominance of non-additive gene action among the hybrids. Among the parents, SSF-1870 and SSF-1883 emerged as consistently good general combiners across several traits, whereas none of the hybrids exhibited consistently high specific combining ability across the majority of the traits studied.

**Conclusion:** Among the parents, the line SSF-1870 and the tester SSF-1883 were found to be good general combiners for most of the traits, including number of secondary branches, number of capitula, harvest index, seed yield per plant, and number of seeds per capitulum.

*Keywords: Safflower; heterosis; general combining ability; specific combining ability; line × tester analysis; seed yield; yield-contributing traits; oil content; hybrid vigour; non-additive gene action.*

## 1. Introduction

Safflower (*Carthamus tinctorius* L.) is an important oilseed crop that is tolerant to heat, severe drought and salinity (Weiss, 1983). Safflower seeds contain 27.5 per cent oil (Ahmed *et al.,* 2016) with high levels of polyunsaturated fatty acids (PUFA) (Weiss, 1983). Safflower is known as "Kusum" (India, Pakistan), derived from the Sanskrit "Kusumbha". It is also called false saffron, bastard saffron, thistle saffron, and dyer's saffron (Chavan, 1961; Weiss, 1983). Safflower belongs to the family Compositae and the subfamily Asteraceae. Among 36 species, *Carthamus tinctorius* L. (2n = 24) is the only cultivated species grown for oil production, and the remaining species are wild. Genetic variation in safflower seed characters related to utilisation has also been documented (Rubis, 1967).

Heterosis, or hybrid vigour, refers to the superior performance of hybrid offspring over their parents for one or more traits and arises from the interaction of additive, dominance, and epistatic genetic effects. It represents the combined influence of both additive and non-additive gene actions in the expression of important agronomic traits (Deokar & Patil, 1979; Deokar *et al*., 1984; Narkhede & Patil, 1987). In safflower, the need for heterosis breeding is increasingly recognised due to the limited scope of yield improvement through conventional selection approaches and the necessity to achieve substantial gains in productivity. Assessing the magnitude of heterosis is therefore essential for identifying superior cross combinations and formulating effective hybrid breeding strategies. However, the exploitation of hybrid vigour depends on both biological feasibility and economic viability. Heterosis breeding could serve as a potential approach to achieve quantum improvements in production and productivity, with the promise of a significant breakthrough in crop yield for commercial agriculture (Knowles, 1989). The presence of considerable heterotic effects in safflower over commercial cultivars highlights the strong possibility and necessity of exploiting heterosis at a commercial level in this crop (Waghmode *et al.,* 2021).

Later, a genetic male sterility system was developed for safflower seed production (Pandya *et al*., 1992), and a dwarf male-sterility system was patented by Weisker (1995). This technique allows for the early and efficient eradication of normal fertile plants due to the pleiotropic effect of the male sterility gene on plant dwarfism. Gibberellic acid (GA3) can be used as a chemical hybridising agent (CHA) for hybrid seed production in safflower (Baydar *et al*., 2003). According to Allard (1960), hybrid vigour is a complex trait, referring to the increased performance of a hybrid compared with the mid-parent value (heterosis) and the better parent (heterobeltiosis). The expression of the trait is influenced by the balance between additive and dominant gene effects, their interactions, and the genetic makeup of the parental lines. Knowledge of the degree and distribution of genetic variation, as well as the relationships among breeding materials, is essential for any crop improvement programme (Shivani *et al*., 2011a). Choosing appropriate parents is crucial for maximising genetic gain and utilising breeding resources. Avoidance of female selfs is also important in hybrid safflower seed production (Urie & Zimmer, 1970). Recent safflower research has continued to document genetic variability among germplasm and the relevance of diverse material for breeding and yield improvement (Govindu *et al*., 2024; Sabaghnia *et al*., 2024; Hamdan, 2024). Genomic-selection simulations have also examined genetic gain for grain yield and oil content in safflower breeding (Zhao *et al*., 2024).

The line x tester method, introduced by Kempthorne (1957), is a commonly employed and efficient mating design for studying the inheritance of quantitative traits. As outlined by Kose (2017), this breeding approach facilitates the estimation of the general combining ability (GCA) of parents and the identification of optimal parents and hybrids with superior specific combining ability (SCA). Heterosis, or hybrid vigour, refers to the enhanced vigour observed in hybrids from individuals within the same or closely related species compared with their parents (Timberlake, 2013). A recent line × tester study in sunflower similarly used GCA and SCA estimates to evaluate gene action for yield and associated traits (Sharma *et al*., 2026).

Combining ability and heterosis play a vital role in developing superior genotypes (Kose, 2017). Numerous studies have evaluated safflower hybrids through the line × tester mating design to improve important breeding traits (Ranga Rao, 1982; Manjare & Jambhale, 1995; Golkar *et al.,* 2012; Nai *et al.,* 2014; Kose, 2017; Kanoje *et al.,* 2018). Despite the available reports on safflower heterosis and combining ability, information remains limited for the specific parental material evaluated here, particularly regarding the concurrent assessment of GCA, SCA, heterosis, seed yield, yield-contributing traits, and oil content under the present experimental conditions. The present investigation was carried out to assess the general combining ability of parental lines, the specific combining ability of their crosses, and the heterotic performance of the resulting hybrids for yield and yield-related traits. Furthermore, the research aimed to identify promising hybrids as potential candidates for developing new high-yielding cultivars with improved oil content and quality.

## 2. Materials and Methods

The experiment was carried out at the Field Experimentation Centre, Department of Genetics and Plant Breeding, SHUATS, Prayagraj (Uttar Pradesh) during 2022-23 and 2023-24. The experimental material comprised nine parental lines and one check variety (Sharda), sourced from Mahatma Phule Krishi Vidyapeeth, Rahuri, and the All India Coordinated Research Project, Parbhani. Four lines (SSF-1371, SSF-708, SSF-1871, SSF-1870) and five testers (SSF-1883, SSF-18123, SSF-1240, SSF-1872, SSF-1704) were crossed in a Line x Tester mating design (Kempthorne, 1957) to obtain 20 crosses during the Rabi 2022-23 season. A total of 20 hybrids, along with the check variety, were evaluated in a randomised block design with three replications having plot size 121.5 m$^2$ with spacing 45 X 30 cm during Rabi 2023-24. Details of safflower hybrids are given in Tables 1 and 2. The morphological observations were recorded for 12 quantitative characters. The data were recorded for days to 50 per cent flowering and days to maturity on a plot basis. The data for the remaining traits were recorded from five randomly selected competitive plants in each genotype per replication for plant height (cm), number of primary branches per plant, number of secondary branches per plant, number of capitula per plant, number of seeds per capitulum, seed index (g), biological yield per plant (g), harvest index, seed yield per plant (g) and oil content (% on a plant basis). The data were subjected to analysis of variance using the technique suggested by Panse and Sukhatme (1967). Combining ability analysis and the testing of significance of different genotypes were based on the procedure given by Kempthorne (1957). The superiority of hybrids was estimated over the mid-parent as average heterosis, over the better parent as heterobeltiosis and over the standard check (Sharda) as standard heterosis according to the method of Fonseca and Patterson (1968). Significance of the GCA, SCA and heterosis estimates was tested against the critical difference (CD) at the 5% probability level, computed using the respective error mean squares from the analysis of variance; values exceeding the CD at 5% and 1% probability levels are denoted by single (*) and double (**) asterisks, respectively, throughout the text and tables. All observations, except days to 50 per cent flowering and days to maturity, which were recorded on a whole-plot basis, were recorded on five randomly selected competitive plants per replication and expressed on a per-plant basis, as stated above.

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

$$Hs\,(\%) = 100 \times (F1 - MP)/MP$$

$$Hb\,(\%) = 100 \times (F1 - HP)/HP$$

$$Hst\,(\%) = 100 \times (F_1 - SC) / SC$$

**Table 1. Experimental material, Source and features of parental lines and check**

| Sr. No. | Parents | Sources | Characters of parental line |
|---|---|---|---|
| **Lines** | | | |
| 1) | SSF-1371 | MPKV, Rahuri | Resistance for aphid |
| 2) | SSF-708 | MPKV, Rahuri | High Oil Content |
| 3) | SSF-1871 | MPKV, Rahuri | High Seed Yielding Variety |
| 4) | SSF-1870 | MPKV, Rahuri | More Number of Seeds Per Capitulum |
| **Testers** | | | |
| 5) | SSF-1883 | MPKV, Rahuri | High yield, Bold capitulum |
| 6) | SSF-18123 | MPKV, Rahuri | High yield, low hull content. |
| 7) | SSF-1240 | MPKV, Rahuri | More Number of Seeds Per Capitulum |
| 8) | SSF-1872 | MPKV, Rahuri | Spiny, Resistance for aphid |
| 9) | SSF-1704 | MPKV, Rahuri | Spiny, High Seed Yielding Variety |
| **Check** | | | |
| 1) | Sharda | AICRP, Parbhani | Spiny, moderately tolerant to aphid and wilt. |

**Table 2. List of crosses**

| Sr. No. | Hybrids | Sr. No. | Hybrids |
|---|---|---|---|
| 01 | SSF-1371×SSF-1883 | 11 | SSF-1871×SSF-1883 |
| 02 | SSF-1371×SSF-18123 | 12 | SSF-1871×SSF-18123 |
| 03 | SSF-1371×SSF-1240 | 13 | SSF-1871×SSF-1240 |
| 04 | SSF-1371×SSF-1872 | 14 | SSF-1871×SSF-1872 |
| 05 | SSF-1371×SSF-1704 | 15 | SSF-1871×SSF-1704 |
| 06 | SSF-708×SSF-1883 | 16 | SSF-1870×SSF-1883 |
| 07 | SSF-708×SSF-18123 | 17 | SSF-1870×SSF-18123 |
| 08 | SSF-708×SSF-1240 | 18 | SSF-1870×SSF-1240 |
| 09 | SSF-708×SSF-1872 | 19 | SSF-1870×SSF-1872 |
| 10 | SSF-708×SSF-1704 | 20 | SSF-1870×SSF-1704 |

## 3. Results and Discussion

Analysis of variance for experimental design: The analysis of variance showed highly significant differences among the 30 genotypes for all the traits studied, indicating the existence of sufficient genetic variability in the experimental material for the manifestation of heterosis and other genetic parameters (Table 3).

**Table 3. Analysis of variance among safflower genotypes for 12 characters**

| Sl. No. | Source | Mean Sum of Squares (MSS) | | |
|---|---|---|---|---|
| | | Replication | Treatment | Error |
| | Degrees of freedom | 2 | 29 | 58 |
| 1 | Days to 50% flowering | 15.7440 | 46.715** | 6.17 |
| 2 | Plant height (cm) | 104.0330 | 113.386** | 52.024 |
| 3 | Days to maturity | 2.2110 | 52.684** | 20.751 |
| 4 | Number of primary branches | 0.1440 | 8.356** | 0.835 |
| 5 | Number of secondary branches | 0.6330 | 34.233** | 3.044 |
| 6 | Number of capitulum | 2.8440 | 47.951** | 6.995 |
| 7 | Number of seeds per capitulum | 0.8280 | 21.907** | 2.785 |
| 8 | Seed Index | 0.2830 | 0.633** | 0.147 |
| 9 | Biological yield (g) | 37.7210 | 1571.334** | 80.74 |
| 10 | Harvest Index (%) | 9.2620 | 63.416** | 7.132 |
| 11 | Oil content (%) | 3.1060 | 23.303** | 1.143 |
| 12 | Seed yield (g) | 9.6040 | 56.619** | 6.702 |

### 3.1 Combining Ability Analysis

Combining ability analysis is a highly effective approach for identifying superior parental lines and their potential in hybridisation programmes. It facilitates the discrimination of good combiners from poor ones and provides valuable insights into the relative importance of general combining ability (GCA) and specific combining ability (SCA). This, in turn, helps to understand the genetic architecture and inheritance patterns governing important agronomic traits such as seed yield and oil content. The conceptual framework for partitioning genetic effects into GCA and SCA components was originally proposed by Sprague and Tatum (1942). The estimates of GCA effects for parental lines and SCA effects for hybrid combinations for yield and its component traits in safflower are presented in Tables 4 and 5.

Analysis of variance for combining ability revealed highly significant differences among crosses for the traits, namely number of capitula per plant, number of seeds per capitulum, biological yield, harvest index, seed yield, and oil content. The mean squares due to lines (female parents) were highly significant for seed yield and oil yield per plant, whereas testers (male parents) did not exhibit significant mean-square effects for most traits. The line × tester interaction effects were found to be highly significant for all the traits studied, except plant height, oil content, and test weight. These findings are in agreement with earlier reports by Ramachandram and Goud (1984), Pandya *et al.* (1990), Patil *et al.* (2002), and Jhajharia *et al.* (2013).

The estimates of SCA variance were greater than those of GCA variance for all the traits studied, and the ratio of GCA to SCA variance was less than unity, indicating the predominance of non-additive gene action. This suggests that the traits under study are largely governed by dominance and epistatic effects. The contribution of lines to total genetic variability was higher than that of testers for traits such as seed index, biological yield, harvest index, seed yield per plant, and oil content. In contrast, testers and line × tester interactions contributed more to the variability of traits such as plant height, number of primary branches, number of secondary branches, number of capitula, number of seeds per capitulum, days to 50% flowering, and days to maturity. These results are consistent with the findings of Ramachandram and Goud (1981) and Untwale *et al.* (1993).

Among the testers, SSF-1883 was identified as the best general combiner for plant height, seed yield, number of secondary branches, number of capitula, and number of seeds per capitulum. The cross SSF-1371×SSF-1883 exhibited superior combining ability for oil content and biological yield per plant. Additionally, the parent SSF-1870 was found to be a good general combiner in the desired direction for number of secondary branches, number of capitula, harvest index, seed yield, and number of seeds per capitulum. These results are in accordance with earlier findings reported by Sadanshio *et al.* (1999a) and Singh *et al.* (2008).

Among the hybrids, SSF-1371×SSF-1883 exhibited the highest SCA effects for biological yield and oil yield per plant, followed by SSF-1371×SSF-1704 for seed yield. The superior performance of these crosses may be attributed to the involvement of parents with high GCA effects, indicating a favourable interaction between additive and non-additive gene effects. Of the 20 crosses evaluated, only one cross exhibited a significant positive SCA effect for seed yield per plant.

### 3.2 Heterosis

Heterosis values estimated as percentages over the mid-parent (relative heterosis), better parent (heterobeltiosis), and standard check Sharda (standard heterosis) for different characters are presented in Table 6.

A total of nine hybrids showed significant positive heterosis for days to 50% flowering for all three bases of heterosis, namely relative heterosis, heterobeltiosis, and standard heterosis. However, the hybrid SSF-708×SSF-1872 recorded significant negative heterosis for this trait, with values of -3.61% (relative heterosis) and -4.41% (heterobeltiosis), showing earliness in flowering compared with its parents. Earliness is often considered a desirable trait in crop improvement programmes, particularly under conditions where early maturity is beneficial. The results obtained in the present investigation are in agreement with the earlier findings of Yazdi-Samadi *et al.* (1975), Deshmukh *et al.* (1991), Manjare and Jambhale (1995), Sadanshio *et al.* (1999b) and Fokmare (2001) for this trait.

**Table 4. Estimation of general combining ability for different characters in safflower**

| **General Combining Ability** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Days to 50% flowering** | **Plant height (cm)** | **Days to maturity** | **Number of primary branches** | **Number of secondary branches** | **Number of capitulum** | **Number of seeds per capitulum** | **Seed Index** | **Biological yield (g)** | **Harvest Index (%)** | **Oil content (%)** | **Seed yield (g)** |
| SSF-708 | -2.233 ** | -2.535 | -2.967 * | 1.130 ** | 0.823 | 0.683 | 0.059 | -0.051 | 8.167 ** | -1.928** | 0.531 | -0.585 |
| SSF-1371 | 0.433 | -0.768 | 3.567 ** | -0.670 ** | -2.017 ** | -1.423 * | 0.167 | 0.37** | 15.487 ** | -3.618** | -0.307 | -1.718 * |
| SSF-1870 | -1.433 * | 3.331 | -1.633 | 0.917 ** | 2.090 ** | 2.257 ** | 1.113 * | -0.009 | -7.593 ** | 3.775 ** | -0.514 | 3.542 ** |
| SSF-1871 | 3.233 ** | -0.028 | 1.033 | -1.377 ** | -0.897 | -1.517 * | -1.339 ** | -0.315** | -16.060 ** | 1.772 * | 0.29 | -1.238 |
| SSF-1240 | -0.633 | -2.218 | 1.433 | 0.930 ** | 0.617 | 1.583 * | -0.566 | 0.101 | 2.52 | 1.797 * | 0.266 | 3.157 ** |
| SSF-1704 | 0.367 | 3.644 | -2.483 | 0.163 | -1.583 ** | -1.767 * | -0.768 | -0.159 | 5.487 * | -4.696 ** | 1.526 ** | -4.568 ** |
| SSF-1872 | -0.883 | -3.343 | 1.433 | -0.487 | -1.667 ** | -3.183 ** | -1.048 * | 0.158 | 8.687 ** | -3.667** | 0.019 | -2.768 ** |
| SSF-1883 | 3.033 ** | 4.64* | 1.35 | -0.487 | 2.483 ** | 2.600 ** | 1.214 * | -0.207 | 1.02 | 2.765 ** | -0.86** | 2.798 ** |
| SSF-18123 | -1.883 * | -2.726 | -1.733 | -0.12 | 0.15 | 0.767 | 1.168 * | 0.107 | -17.713 ** | 3.802 ** | -0.94** | 1.382 |

**Table 5. Estimation of specific combining ability for different characters in safflower**

| **Specific Combining Ability** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Days to 50% flowering** | **Plant height (cm)** | **Days to maturity** | **Number of primary branches** | **Number of secondary branches** | **Number of capitulum** | **Number of seeds per capitulum** | **Seed Index** | **Biological yield (g)** | **Harvest Index (%)** | **Oil content (%)** | **Seed yield (g)** |
| SSF-708×SSF-1240 | 0.567 | -2.558 | 0.3 | -1.730 ** | -5.190 ** | -4.517 ** | 1.273 | 0.111 | 3.333 | 1.272 | -2.094 ** | 2.177 |
| SSF-708×SSF-1704 | 1.567 | -7.083 | 0.217 | 4.303 ** | 3.743 ** | 2.033 | -1.525 | -0.533 * | 0.033 | 2.529 | -0.351 | 2.502 |
| SSF-708×SSF-1872 | -6.183 ** | -2.763 | -4.7 | -2.047 ** | -1.04 | -0.017 | -2.644 * | 0.301 | -8.367 | -0.22 | 0.996 | -2.365 |
| SSF-708×SSF-1883 | -0.1 | 11.385 * | 0.717 | 0.42 | 2.877 ** | 1.333 | 3.690 ** | -0.251 | 0.833 | -2.585 | -0.978 | -2.132 |
| SSF-708×SSF-18123 | 4.150 ** | 1.02 | 3.467 | -0.947 | -0.39 | 1.167 | -0.793 | 0.372 | 4.167 | -0.996 | 2.427 ** | -0.182 |
| SSF-1371×SSF-1240 | -0.767 | 5.908 | -1.567 | 1.403 * | -1.95 | -5.477 ** | -2.568 * | -0.397 | -16.253 ** | -2.471 | 1.587 * | -5.890 ** |
| SSF-1371×SSF-1704 | 1.233 | -3.31 | 2.35 | -1.163 * | 1.117 | 1.607 | 1.898 | 0.365 | 7.38 | 3.542 * | -2.983 ** | 4.635 ** |
| SSF-1371×SSF-1872 | 1.15 | 3.133 | 0.433 | -0.313 | 1.133 | 5.023 ** | 2.452 * | 0.042 | -17.487 ** | 1.143 | -2.659 ** | -1.698 |
| SSF-1371×SSF-1883 | 1.9 | -7.915 | -0.817 | 0.02 | -1.283 | -1.76 | -5.218 ** | 0.044 | 30.847 ** | -1.989 | 2.530 ** | 3.002 |
| SSF-1371×SSF-18123 | -3.517 * | 2.183 | -0.4 | 0.053 | 0.983 | 0.607 | 3.436 ** | -0.053 | -4.487 | -0.226 | 1.525 * | -0.048 |
| SSF-1870×SSF-1240 | 1.767 | -5.888 | -2.367 | 0.55 | 5.677 ** | 6.177 ** | -0.048 | 0.173 | 1.293 | 1.183 | -0.009 | 1.083 |
| SSF-1870×SSF-1704 | -2.9 | 8.784 * | -2.117 | -2.483 ** | -4.923 ** | -3.607 * | -0.513 | -0.771 ** | -20.873 ** | -2.691 | 0.964 | -6.025 ** |
| SSF-1870×SSF-1872 | 2.35 | 1.237 | 2.633 | 0.833 | -1.24 | -5.523 ** | -1.895 | 0.259 | 17.660 ** | -0.546 | 2.492 ** | 2.308 |
| SSF-1870×SSF-1883 | -1.9 | -3.551 | -0.617 | 0.3 | -0.123 | 1.893 | 4.769 ** | 0.124 | -2.073 | 0.025 | -1.056 | 0.542 |
| SSF-1870×SSF-18123 | 0.683 | -0.583 | 2.467 | 0.8 | 0.61 | 1.06 | -2.314 * | 0.214 | 3.993 | 2.028 | -2.392 ** | 2.092 |
| SSF-1871×SSF-1240 | -1.567 | 2.538 | 3.633 | -0.223 | 1.463 | 3.817 * | 1.342 | 0.113 | 11.627 * | 0.016 | 0.516 | 2.63 |
| SSF-1871×SSF-1704 | 0.1 | 1.609 | -0.45 | -0.657 | 0.063 | -0.033 | 0.14 | 0.939 ** | 13.460 * | -3.380 * | 2.370 ** | -1.112 |
| SSF-1871×SSF-1872 | 2.683 | -1.607 | 1.633 | 1.527 ** | 1.147 | 0.517 | 2.088 * | -0.602 ** | 8.193 | -0.377 | -0.83 | 1.755 |
| SSF-1871×SSF-1883 | 0.1 | 0.081 | 0.717 | -0.74 | -1.47 | -1.467 | -3.242 ** | 0.083 | -29.607 ** | 4.548 ** | -0.497 | -1.412 |
| SSF-1871×SSF-18123 | -1.317 | -2.621 | -5.533 * | 0.093 | -1.203 | -2.833 | -0.328 | -0.533 * | -3.673 | -0.806 | -1.560 * | -1.862 |
| CD 95% SCA | 2.915 | 8.527 | 5.399 | 1.085 | 2.065 | 3.124 | 1.984 | 0.448 | 10.682 | 3.156 | 1.264 | 3.036 |

Days to maturity is an important component trait contributing to seed yield per plant. In the present study, nine hybrids exhibited positive heterosis over the mid-parent. The magnitude of mid-parent heterosis ranged from -2.10% (SSF-1870×SSF-1704) to 8.61% (SSF-1371×SSF-1872). Moreover, six hybrids showed significant positive heterobeltiosis, while nine crosses exhibited significant standard heterosis over the check variety for this trait. The presence of positive heterosis for days to maturity suggests the potential of these hybrids for prolonged growth duration, which may contribute to enhanced biomass accumulation and yield under favourable conditions. The findings are in accordance with the results reported by Hatamzadeh (2013) for this trait.

Plant height is an important morphological trait that affects plant architecture and yield potential. In the present investigation, the SSF-708×SSF-1883 hybrid exhibited significant positive heterosis over the mid-parent, while the SSF-1870×SSF-1240 hybrid showed significant negative heterosis over the better parent. The cross SSF-708×SSF-1883 recorded significant positive mid-parent heterosis (15.04%), indicating increased plant height. The cross SSF-1870×SSF-1240 manifested significant positive standard heterosis for seed yield, while simultaneously recording desirable negative standard heterosis (-0.50%) for plant height, resulting in an intermediate plant stature. This moderate plant height is agronomically advantageous, as it enhances lodging resistance while successfully sustaining high grain yield potential. Similar results were reported by Yazdi-Samadi *et al.* (1975) and Ahmed *et al.* (2015) for plant height in safflower.

For the number of primary branches per plant, the cross SSF-708×SSF-1704 exhibited high and significant positive heterosis over the mid-parent (53.85**), better parent (41.03**), and standard check Sharda (46.67**), indicating strong hybrid vigour for this trait, which could contribute to greater branching and potentially higher yield in this combination. Similar results were reported by Satpute *et al.* (2011), Singh *et al.* (2008), Fokmare (2001) and Pandya *et al.* (1992).

For the number of secondary branches per plant, the cross SSF-1870×SSF-1240 exhibited high and significant positive heterosis over the mid-parent (32.38**), better parent (24.16**), and standard check Sharda (17.46*), indicating strong hybrid vigour for this trait, which could contribute to greater branching architecture and potentially higher yield potential in this combination. Similar results were found by Patil and Narkhede (1996), Manjare and Jambhale (1995), and Kulkarni *et al.* (1992).

For the number of capitula per plant, the cross SSF-1870×SSF-1240 exhibited high and significant positive heterosis over the mid-parent (38.93**), better parent (28.64**), and standard check Sharda (23.83**), indicating strong hybrid vigour for this trait and suggesting that this cross possesses superior combining ability for capitulum production, which is a key yield-contributing trait in safflower. Similar results were found by Bhakre and Ghorpade (2011) and Shivani *et al.* (2011b).

Number of seeds per capitulum is a key component trait influencing seed yield and plays an important role in enhancing yield potential. In the present study, the cross SSF-1870×SSF-1883 recorded the highest significant positive heterosis over both the mid-parent (46.94 **) and better parent (46.94 **) in the desirable direction. Similar results were found by Ramachandram and Goud (1984), Narkhede *et al.* (1986), Deedawat *et al.* (2016), Ahmed *et al.* (2015), and Shivani *et al.* (2011b).

Seed index is an important component trait contributing to seed yield per plant. Eight hybrids exhibited significant positive heterosis over the mid-parent. For heterobeltiosis, three hybrids showed significant positive heterosis, namely SSF-1371× SSF-1240 (11.04 *), SSF-1371×SSF-1704 (11.33*) and SSF-1870×SSF-1240 (11.62*), while three exhibited significant negative heterosis, namely SSF-1871×SSF-18123 (-17.71**), SSF-1871×SSF-1872 (-13.42**) and SSF-1870×SSF-1704 (-12.70*). In terms of standard heterosis over the check variety Sharda, two hybrids recorded significant positive heterosis, namely SSF-1371×SSF-1704 (10.06 *) and SSF-1371×SSF-1872 (9.95*). Similar results were found by Deedawat *et al.* (2016) and Ahmed *et al.* (2015).

Biological yield is an important component trait contributing to seed yield per plant. Seventeen hybrids exhibited positive heterosis over the mid-parent, of which 14 showed significant positive heterosis. The highest mid-parent heterosis (90.88%) was recorded by the cross SSF-1371×SSF-1883 (90.88 **). For heterobeltiosis, 13 hybrids exhibited significant positive heterosis, while eight out of 20 hybrids showed significant positive standard heterosis over the check for this trait.

Harvest index is an important trait reflecting the efficiency of partitioning assimilates towards economic yield. The cross SSF-1870×SSF-18123 exhibited significant positive heterosis over all three types of heterosis. Overall, ten hybrids showed heterosis in the positive direction, of which three were significant. The SSF-1870×SSF-18123 (58.53**) hybrid recorded significant positive heterobeltiosis, while three out of 24 hybrids exhibited significant positive standard heterosis for this trait.

Oil content is an important quality trait in safflower. Ten hybrids exhibited negative heterosis over the mid-parent. Heterobeltiosis ranged from -22.08% (SSF-708×SSF-1240) to 31.41% (SSF-1870×SSF-1872). Among the 20 hybrids, seven showed significant negative heterosis for the mid-parent, while four crosses recorded significantly higher standard heterosis over the check. Similar results were found by Narkhede *et al.* (1986) and Satpute *et al.* (2011).

Seed yield per plant is the most important economic trait. Nine hybrids exhibited significant positive heterosis over the mid-parent, with values ranging from -21.93% (SSF-1871×SSF-1704) to 67.84% (SSF-1870×SSF-18123). The highest heterobeltiosis (60.30%) was also recorded in the cross SSF-1870×SSF-18123, and seven hybrids showed significant positive heterobeltiosis. Additionally, three hybrids exhibited significant positive standard heterosis for this trait. On the basis of superior yield performance, the cross SSF-1870×SSF-18123 was identified as the best hybrid and selected for further genetic studies in subsequent generations. Similar results were found by Deokar and Patil (1979), Ranga Rao (1982), Ramachandram and Goud (1982), Deokar *et al.* (1984), Ramachandram and Goud (1984), Ratnaparkhi *et al.* (2015) and Shivani *et al.* (2011b).

**Table 6. Estimation of heterosis for various traits in safflower hybrids**

| Cross | Days to 50% flowering | | | Plant height (cm) | | | Days to maturity | | | Number of primary branches | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mid | Better | Std check | Mid | Better | Std check | Mid | Better | Std check | Mid | Better | Std check |
| SSF-708×SSF-1240 | 3.52 * | 3.08 | 4.55 * | 0.62 | -2.78 | -2.5 | 2.24 | 1.88 | 4.83 | -3.09 | -12.42 | -6 |
| SSF-708×SSF-1704 | 4.03 ** | 3.31 | 6.25 ** | -1.22 | -7.05 | -1.45 | -0.82 | -1.4 | 1.93 | 53.85 ** | 41.03 ** | 46.67 ** |
| SSF-708×SSF-1872 | -3.61 * | -4.41 * | -1.42 | -2.37 | -7.33 | -3.55 | -0.83 | -0.95 | 1.21 | -17.86 * | -23.33 ** | -23.33 ** |
| SSF-708×SSF-1883 | 4.43 ** | 3.29 | 7.10 ** | 15.04 ** | 8.96 | 13.92 ** | 2.96 | 2.84 | 5.07 | 15.15 * | 13.43 | 1.33 |
| SSF-708×SSF-18123 | 4.75 ** | 4.46 * | 6.53 ** | 3.97 | 1.23 | -0.08 | 3.09 | 2.6 | 4.83 | -2.49 | -9.27 | -8.67 |
| SSF-1371×SSF-1240 | 3.77 * | 2.48 | 5.68 ** | 3.45 | 1.7 | 5.58 | 6.67 ** | 5.16 | 8.21 ** | 19.26 * | 0 | 7.33 |
| SSF-1371×SSF-1704 | 5.10 ** | 4.96 ** | 8.24 ** | -1.9 | -2.92 | 2.93 | 6.41 ** | 4.67 | 8.21 ** | -16.23 * | -28.85 ** | -26.00 ** |
| SSF-1371×SSF-1872 | 3.86 * | 3.86 * | 7.10 ** | -1.4 | -1.52 | 2.5 | 8.61 ** | 7.58 ** | 9.66 ** | -11.97 | -24.00 ** | -24.00 ** |
| SSF-1371×SSF-1883 | 7.42 ** | 7.12 ** | 11.08 ** | -3.94 | -4.28 | 0.08 | 7.66 ** | 6.64 * | 8.70 ** | -2.06 | -11.19 | -20.67 ** |
| SSF-1371×SSF-18123 | -0.28 | -0.83 | 2.27 | 0.96 | -1.52 | 2.23 | 6.12 * | 5.49 * | 6.76 * | -3.85 | -17.22 * | -16.67 * |
| SSF-1870×SSF-1240 | 3.74 * | 1.91 | 6.25 ** | -5.48 | -9.74 * | -0.5 | 0.7 | 0.47 | 3.86 | 21.99 ** | 6.83 | 14.67 |
| SSF-1870×SSF-1704 | -0.41 | -1.09 | 3.13 | 7.01 | 4.96 | 15.71 ** | -2.1 | -2.1 | 1.21 | -16.97 * | -26.28 ** | -23.33 ** |
| SSF-1870×SSF-1872 | 2.74 | 2.18 | 6.53 ** | -2.73 | -5.45 | 4.24 | 4.71 * | 3.97 | 7.49 ** | 14.39 | 3.33 | 3.33 |
| SSF-1870×SSF-1883 | 2.19 | 1.91 | 6.25 ** | -0.59 | -3.16 | 6.76 | 2.35 | 1.64 | 5.07 | 15.29 | 9.7 | -2 |
| SSF-1870×SSF-18123 | 1.1 | 0 | 4.26 * | -1.14 | -6.31 | 3.29 | 2.72 | 1.64 | 5.07 | 17.65 * | 5.96 | 6.67 |
| SSF-1871×SSF-1240 | 6.63 ** | 6.48 ** | 7.39 ** | 1.47 | -0.2 | 3.5 | 7.29 ** | 7.04 * | 10.14 ** | -16.00 * | -21.74 ** | -16.00 * |
| SSF-1871×SSF-1704 | 7.67 ** | 6.63 ** | 9.66 ** | 2.41 | 1.29 | 7.4 | 1.41 | 0.93 | 4.35 | -26.78 ** | -30.77 ** | -28.00 ** |
| SSF-1871×SSF-1872 | 8.64 ** | 7.44 ** | 10.80 ** | -4.39 | -4.55 | -0.66 | 6.38 ** | 6.13 * | 8.70 ** | -9.34 | -12.67 | -12.67 |
| SSF-1871×SSF-1883 | 9.44 ** | 7.95 ** | 11.93 ** | 2.73 | 2.32 | 6.98 | 5.67 * | 5.42 * | 7.97 ** | -28.94 ** | -30.22 ** | -35.33 ** |
| SSF-1871×SSF-18123 | 5.04 ** | 4.46 * | 6.53 ** | -2.16 | -4.52 | -0.97 | -0.59 | -1.18 | 1.21 | -20.69 ** | -23.84 ** | -23.33 ** |

**Table 6. Contd..**

| Cross | Number of secondary branches | | | Number of capitulum | | | Number of seeds per capitulum | | | Seed Index | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mid | Better | Std check | Mid | Better | Std check | Mid | Better | Std check | Mid | Better | Std check |
| SSF-708×SSF-1240 | -21.83 ** | -36.91 ** | -40.32 ** | -3.08 | -16.02 | -19.16 * | 8.98 | -0.86 | 8.63 | 11.51 * | 10.46 | 3.49 |
| SSF-708×SSF-1704 | 35.36 ** | 18.44 * | -8.25 | 20.86 * | 12.57 | -7.94 | 4.24 | 3.51 | -5.75 | -7.17 | -9.59 | -10.63 * |
| SSF-708×SSF-1872 | 0.7 | -12.2 | -31.43 ** | 3.48 | -4.74 | -20.09 * | -2.83 | -3.16 | -12.46 | 9.20 * | 4.3 | 7.35 |
| SSF-708×SSF-1883 | 34.53 ** | 5.97 | 6.98 | 29.02 ** | 13.96 | 4.91 | 39.67 ** | 36.13 ** | 28.74 ** | -4.98 | -8.88 | -6.98 |
| SSF-708×SSF-18123 | 6.3 | -13.65 | -19.68 ** | 20.23 * | 6.08 | -2.1 | 16.93 * | 14.73 * | 7.03 | 6.44 | -0.86 | 7.66 |
| SSF-1371×SSF-1240 | -22.24 ** | -34.90 ** | -38.41 ** | -15.61 | -27.18 ** | -29.91 ** | -7.63 | -17.19 ** | -9.27 | 11.10 * | 11.04 * | 2.19 |
| SSF-1371×SSF-1704 | -6.97 | -15.16 | -34.29 ** | 9.71 | 1.71 | -16.82 * | 24.94 ** | 22.09 ** | 11.17 | 15.32 ** | 11.33 * | 10.06 * |
| SSF-1371×SSF-1872 | -7.83 | -16.26 | -34.60 ** | 17.33 | 7.52 | -9.81 | 26.88 ** | 24.42 ** | 12.48 | 12.80 ** | 6.84 | 9.95 * |
| SSF-1371×SSF-1883 | -10.6 | -27.04 ** | -26.35 ** | 7.07 | -5.84 | -13.32 | -4.6 | -8.46 | -13.43 | 7.44 | 2.14 | 4.27 |
| SSF-1371×SSF-18123 | -6.48 | -21.16 ** | -26.67 ** | 9.22 | -4.05 | -11.45 | 41.86 ** | 37.00 ** | 27.81 ** | 7.32 | -0.86 | 7.66 |
| SSF-1870×SSF-1240 | 32.38 ** | 24.16 ** | 17.46 * | 38.93 ** | 28.64 ** | 23.83 ** | 5.17 | -2.03 | 7.35 | 12.97 ** | 11.62 * | 5.11 |
| SSF-1870×SSF-1704 | -29.50 ** | -31.80 ** | -43.49 ** | -4.99 | -5.13 | -22.20 ** | 12.22 | 10.14 | 4.15 | -10.58 * | -12.70 * | -13.71 ** |
| SSF-1870×SSF-1872 | -8.48 | -11.11 | -26.35 ** | -20.28 * | -21.17 * | -33.88 ** | 4 | 1.71 | -3.82 | 8.94 * | 4.3 | 7.35 |

| Cross | Number of secondary branches | | | Number of capitulum | | | Number of seeds per capitulum | | | Seed Index | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mid | Better | Std check | Mid | Better | Std check | Mid | Better | Std check | Mid | Better | Std check |
| SSF-1870×SSF-1883 | 7.43 | -2.2 | -1.27 | 29.13 ** | 22.08 * | 12.38 | 46.94 ** | 46.94 ** | 38.96 ** | 1.43 | -2.5 | -0.47 |
| SSF-1870×SSF-18123 | 3.61 | -2.05 | -8.89 | 18.23 * | 11.65 | 3.04 | 11.56 | 10.81 | 4.79 | 4.39 | -2.54 | 5.84 |
| SSF-1871×SSF-1240 | 8.04 | -12.08 | -16.83 * | 27.14 ** | 6.31 | 2.34 | 0.18 | -6.68 | 2.25 | 3.92 | 0.05 | -0.63 |
| SSF-1871×SSF-1704 | -3.48 | -14.75 | -33.97 ** | 5.26 | -5.71 | -22.90 ** | 2.93 | 1.01 | -4.47 | 9.23 * | 8.97 | 8.23 |
| SSF-1871×SSF-1872 | 3 | -9.35 | -29.21 ** | -0.31 | -11.7 | -25.93 ** | 11.93 | 9.46 | 3.51 | -11.88 ** | -13.42 ** | -10.89 * |
| SSF-1871×SSF-1883 | -2.57 | -22.64 ** | -21.90 ** | 11.48 | -5.08 | -12.62 | -6.08 | -6.08 | -11.18 | -6.55 | -7.81 | -5.89 |
| SSF-1871×SSF-18123 | -10.42 | -26.62 ** | -31.75 ** | -2.98 | -17.47 * | -23.83 ** | 9.18 | 8.45 | 2.56 | -14.04 ** | -17.71 ** | -10.63 * |

**Table 6. Contd..**

| Cross | Biological yield (g) | | | Harvest Index (%) | | | Oil content (%) | | | Seed yield (g) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mid | Better | Std check | Mid | Better | Std check | Mid | Better | Std check | Mid | Better | Std check |
| SSF-708×SSF-1240 | 44.68 ** | 23.53 ** | 21.52 ** | -8.88 | -23.33 * | -5.49 | -17.97 ** | -22.08 ** | -4.46 | 37.28 ** | 34.93 ** | 14.7 |
| SSF-708×SSF-1704 | 38.87 ** | 23.23 ** | 21.23 ** | -29.30 ** | -37.28 ** | -31.80 ** | -2.4 | -4.18 | 5.73 | 0.53 | 0.35 | -17.61 |
| SSF-708×SSF-1872 | 20.05 ** | 18.63 ** | 16.71 * | -32.82 ** | -36.05 ** | -40.44 ** | 9.83 ** | -4.67 | 5.19 | -18.7 | -21.26 | -31.00 ** |
| SSF-708×SSF-1883 | 30.62 ** | 19.99 ** | 18.04 ** | -13.27 | -20.23 | -20.01 | -9.40 ** | -13.47 ** | -4.51 | 14.69 | 14.49 | -5.68 |
| SSF-708×SSF-18123 | 11.08 | 6.37 | 4.64 | 9.24 | 7.81 | -6.81 | 6.93 * | -3.24 | 6.77 * | 20.95 * | 17.73 | -3.35 |
| SSF-1371×SSF-1240 | 52.94 ** | 47.11 ** | 10.85 | -33.40 ** | -45.47 ** | -32.79 ** | -8.77 ** | -14.21 ** | 5.19 | 3.43 | -12.33 | -25.47 ** |
| SSF-1371×SSF-1704 | 76.81 ** | 75.80 ** | 33.99 ** | -30.81 ** | -40.41 ** | -35.20 ** | -12.32 ** | -13.00 ** | -6.04 | 23.14 * | 6.05 | -13.25 |
| SSF-1371×SSF-1872 | 34.35 ** | 19.87 ** | 15.14 * | -32.54 ** | -37.81 ** | -42.08 ** | -4.93 | -16.71 ** | -10.06 ** | -8.73 | -23.59 * | -33.04 ** |
| SSF-1371×SSF-1883 | 90.88 ** | 82.75 ** | 50.52 ** | -16.69 | -25.70 * | -25.50 * | 0.32 | -3.19 | 4.55 | 58.02 ** | 35.69 ** | 11.79 |
| SSF-1371×SSF-18123 | 25.15 ** | 14.95 * | 3.48 | 7.34 | 2.46 | -11.44 | 2.22 | -6.60 * | 0.87 | 34.89 ** | 18.73 | -7.71 |
| SSF-1870×SSF-1240 | 25.08 ** | 6.09 | 6.03 | 26.35 * | -0.45 | 22.71 * | -1.91 | -19.20 ** | -0.93 | 64.30 ** | 50.51 ** | 27.95 ** |
| SSF-1870×SSF-1704 | 1.42 | -10.62 | -10.67 | -21.4 | -35.05 ** | -29.37 * | 14.85 ** | 0.31 | 6.65 * | -17.18 | -22.78 | -36.83 ** |
| SSF-1870×SSF-1872 | 28.20 ** | 25.71 ** | 25.64 ** | 5.5 | -7.05 | -13.43 | 32.89 ** | 31.41 ** | 6.72 * | 35.66 ** | 22.59 * | 7.42 |
| SSF-1870×SSF-1883 | 11.68 | 1.86 | 1.8 | 42.20 ** | 21.42 | 21.75 | 1.95 | -8.73 ** | -8.33 ** | 61.98 ** | 50.53 ** | 24.02 * |
| SSF-1870×SSF-18123 | -4.43 | -9.17 | -9.22 | 74.10 ** | 58.53 ** | 37.03 ** | 2.96 | -2.77 | -13.12 ** | 67.84 ** | 60.30 ** | 24.60 * |
| SSF-1871×SSF-1240 | 52.88 ** | 51.14 ** | 7.66 | -10.6 | -13.37 | 6.78 | -9.17 ** | -15.52 ** | 3.58 | 36.71 ** | 33.90 ** | 13.83 |
| SSF-1871×SSF-1704 | 51.69 ** | 46.73 ** | 11.83 | -49.10 ** | -50.61 ** | -42.89 ** | 7.79 ** | 7.36 * | 14.15 ** | -21.93 * | -22.06 | -36.24 ** |
| SSF-1871×SSF-1872 | 31.55 ** | 14.55 * | 10.03 | -25.89 ** | -33.10 ** | -22.64 * | 5.18 | -6.91 * | -1.82 | -0.52 | -3.99 | -15.87 |
| SSF-1871×SSF-1883 | -8.23 | -14.44 | -29.52 ** | 24.51 ** | 16.24 | 34.41 ** | -6.46 * | -8.70 ** | -3.7 | 15.45 | 14.84 | -5.39 |
| SSF-1871×SSF-18123 | -4.82 | -14.76 * | -23.26 ** | 11.57 | -2.51 | 12.72 | -5.11 | -12.36 ** | -7.57 * | 8.59 | 6.07 | -13.54 |

## 4. Limitations of the Study

The present findings are based on the evaluation of the F1 hybrids in a single crop season (Rabi 2023-24) at one location, and the parental heterosis was estimated using per se performance data recorded from the same trial; consequently, the promising cross combinations identified here reflect single-environment hybrid vigour rather than confirmed commercial potential. Multi-location and multi-season evaluation of the superior hybrids, together with assessment of heterosis stability across environments and confirmation of the genetic purity and seed-setting behaviour of the male-sterile/restorer system prior to commercial exploitation, is therefore recommended before these hybrids are advanced for large-scale cultivation.

## 5. Conclusion

Combining ability analysis identified SSF-1870 and SSF-1883 as good general combiners for eight traits each, including seed yield, reflecting the predominance of additive gene effects in governing these characters. However, the lack of consistent association between per se performance and SCA effects in crosses such as SSF-1871×SSF-1240 and SSF-1870×SSF-1883 suggests that SCA effects alone are insufficient as a selection criterion, and per se performance of hybrids may serve as a more reliable basis for identifying superior combinations. Heterosis analysis revealed substantial hybrid vigour for seed yield, with maximum heterobeltiosis and standard heterosis of 60.30% and 27.95%, respectively. Crosses SSF-1870×SSF-18123, SSF-1870×SSF-1883, and SSF-1870×SSF-1240 exhibited significant positive standard heterosis over the check variety 'Sharda', coupled with superior mean seed yield, underscoring the role of non-additive gene action in these combinations. The consistent performance of SSF-1870 across both GCA and heterosis analyses highlights its utility as a potential parent for exploitation in safflower hybrid breeding programmes aimed at enhancing seed yield.

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## Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

## Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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