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Estimation of Heterosis and Combining Ability in Different Sunflower Genotypes Using Line × Tester Analysis

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Abstract

One important oilseed crop that could help with the scarcity of edible oil is the sunflower (Helianthus annuus L.). This study used a Line × Tester mating design to assess sunflower heterosis and combining ability. Twelve F_1 hybrids were created by crossing four elite inbred lines (HZ-6, HZ-7, HZ-8, and HZ-9) with three testers (PBG-1, PBG-2, and PBG-3). In two seasons (fall 2023 and spring 2024), the parents and hybrids were cultivated using a randomized complete block design with three replications. Plant height, number of leaves per plant, leaf area, internodal length, stem diameter, head diameter, seed yield per head, and 100-seed weight were the eight yield-related characteristics for which data were collected. Significant genetic differences between genotypes for every trait were found by analysis of variance. According to line × tester analysis, non-additive (dominant) gene action predominated for the majority of traits, with specific combining ability (SCA) variance exceeding general combining ability (GCA) variance. Strong GCA effects were seen for important traits (e.g. internodal length, head diameter, seed yield) in the parental lines HZ-6 and HZ-9. Combinations like HZ-6 × PBG-3 and HZ-8 × PBG-1 performed better than other hybrids; HZ-6 × PBG-3 was superior in terms of stem diameter and leaf area, while HZ-8 × PBG-1 was superior in terms of plant height and 100-seed weight. Several traits (most notably head diameter and seed yield) showed positive mid-parent and better-parent heterosis, whereas traits such as internode length, stem diameter, and seed weight showed negative heterosis. These findings imply that sunflower breeding can benefit from hybrid vigour. The high-GCA parents and high-SCA hybrids that have been identified provide useful breeding material for creating improved sunflower cultivars that may increase yield and help lessen the edible oil deficit.

Keywords: Heterosis, Combining, Sunflower, Genotypes, Tester Analysis

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Introduction

After soybean, groundnut, and rapeseed, sunflower is the fourth most important oilseed crop in the world. It is a valuable source of edible oil because its seeds produce high-quality oil that is high in vitamins and unsaturated fatty acids (Rani et al., 2017). As a short-duration crop that can be grown in the spring and fall, sunflower has drawn interest in Pakistan as a way to close the gap between domestic oil production and consumption. However, because of things like inadequate agronomic methods, low-quality seeds, and a dearth of high-yielding hybrids that are adapted, Pakistan's average sunflower yields are still low at about 1000 kg per acre. Improving sunflower hybrids is essential for raising farmer profitability and productivity, which will lessen dependency on imported edible oil (Arshad et al., 2020).

Two important genetic ideas used in crop improvement are heterosis (hybrid vigour) and combining ability. The term "heterosis" describes how hybrids perform better than their parents for a given trait, frequently leading to improved agronomic traits or a higher yield. Combining ability, which is measured as specific combining ability (SCA) for non-additive gene effects and general combining ability (GCA) for additive gene effects, is the ability of a parent line to pass on desired traits to its progeny. By crossing a set of "line" parents with a set of "tester" parents, a breeding experimental design known as a Line × Tester analysis (Kempthorne, 1957) assesses GCA and SCA. This technique assists in identifying particular hybrid combinations that perform exceptionally well, as well as parental lines that make good general combiners. Prior research on sunflowers has demonstrated that line × tester mating can capture significant genetic variability and that yield-related traits are frequently dominated by non-additive gene action. For example, Azad et al. (2016) discovered that for the majority of sunflower yield traits, non-additive effects predominated. However, some traits might also exhibit significant additive effects, highlighting the necessity of evaluating both GCA and SCA in breeding populations.

In the current study, we used a line × tester approach to estimate the degree of heterosis and combining ability in a set of sunflower genotypes. We aim to find promising parent lines and hybrid combinations for creating high-yielding sunflower varieties by assessing hybrid performance and gene action for yield and its constituent parts. By shedding light on the genetic makeup of yield traits and identifying superior genotypes that can hasten hybrid development, this study aids in the breeding of sunflowers in Pakistan and around the world.

Materials and Methods

Plant Material and Crossing Design:

The experiment was carried out at the University of Agriculture, Faisalabad, Pakistan's Plant Breeding and Genetics research area. Seven sunflower genotypes were chosen from the department's breeding program to make up the genetic material: three male testers (PBG-1, PBG-2, and PBG-3) and four female inbred lines (HZ-6, HZ-7, HZ-8, and HZ-9). To generate F_1 hybrids, all parent lines were planted and crossed in a line × tester fashion in the fall of 2023. Using each of the three testers, each of the four lines was hand-pollinated, resulting in 12 different crosses (e.g., HZ-6 × PBG-1, HZ-6 × PBG-2, …, HZ-9 × PBG-3). In order to guarantee fertilization, pollen from tester plants was sprinkled onto receptive stigmas over the course of two to three mornings. Female heads were bagged once the anthers were manually removed. This was done in accordance with standard emasculation and controlled pollination procedures. Each successful cross's seeds were collected and kept apart.

Field Evaluation:

To assess the performance of the 12 F_1 hybrids and their 7 parents, they were cultivated in the field in the spring of 2024. Three replicates were used in the randomized complete block design (RCBD) experiment. Plants were spaced 25 cm within rows and 75 cm between rows in each plot, which had one row per entry. Agronomic management techniques were consistent across all plots; to reduce environmental variance, recommended fertilizer rates were applied, along with timely irrigations, weed control, and pest protection measures. There were no extreme biotic or abiotic stressors that could have a different impact on the entries. Three representative plants from each plot were tagged for data collection once they reached physiological maturity.

Data collection:

Eight quantitative traits related to growth and yield were observed: (1) plant height (cm), which was measured from the base of the stem to the top of the capitulum; (2) number of leaves per plant, which was counted on each sample plant; (3) leaf area (cm2), which was calculated for fully expanded leaves using length × width measurements and a calibration factor; (4) internodal length (cm), which is the average length between consecutive nodes on the stem; (5) stem diameter (cm), which was measured at mid-height of the stem using calipers; (6) head diameter (cm), which was measured across the face of the capitulum; (7) seed yield per head (g), which is the total weight of seeds (achenes) produced by a plant; and (8) 100-seed weight (g), which is the weight of a random sample of 100 seeds as a measure of seed size. To guarantee accurate estimations, the average of three plants was used for each trait value per plot.

Statistical Analysis:

To determine whether there were significant differences between the genotypes (parents and hybrids) for each trait, the gathered data were subjected to analysis of variance (ANOVA) using the RCBD model (Steel et al., 1997). Statistical significance was defined as a p-value of less than 0.05, and highly significant differences were indicated by a p-value of less than 0.01. In order to estimate the general and specific combining ability effects, the treatment sum of squares was divided into components due to lines, testers, and line×tester interaction using the line × tester mating design (method of Kempthorne, 1957). Using standard formulas based on hybrid performance in relation to the overall mean, GCA effects were calculated for each tester and parental line, and SCA effects for each cross. Using t-tests against the error mean square, the significance of the GCA and SCA effects was evaluated. For each trait, the ratio of SCA variance to GCA variance was analyzed as a measure of the dominant gene action (non-additive dominance effects are indicated by an SCA/GCA ratio > 1). Furthermore, each hybrid's heterosis was assessed as the percentage change in the F_1 hybrid relative to its mid-parent value (mid-parent heterosis) and to the parent that performed better (better-parent heterosis). Whereas negative heterosis suggests the hybrid was less proficient than the parent(s) for that trait, positive heterosis shows the hybrid outperformed the parent(s). To determine the best-performing genotypes for each trait, mean comparisons were carried out where appropriate and all statistical analyses were carried out using the appropriate statistical software.

Results

Genetic Variability and Analysis of Variance

For every trait measured, there were highly significant differences between the sunflower genotypes (parents and hybrids), indicating a high level of genetic variability in the test material. Each trait's ANOVA verified that the genotype-based variation (combined parents and crosses) was significant ($p < 0.01$). For instance, the mean squares for crosses and genotypes in plant height were both significant, suggesting that the 12 hybrids had significant differences in stature. The three testers also displayed significant variation, though generally less than the lines, and all four line parents differed significantly from one another for every trait. Crucially, the line × tester interaction was significant for each trait (at $p < 0.01$), indicating that the trait value was uniquely impacted by the particular pairing of a given line with a particular tester. This suggests that particular parental pairings produced particularly advantageous (or unfavourable) results rather than hybrid performance being merely predictable from additive parental effects.

Together, these findings show that there was a significant amount of genetic diversity in the breeding material and that hybridization produced new variation for traits related to yield. The existence of particular combining ability effects and possible heterotic responses is suggested by the significance of line × tester interactions across all traits. Additionally, it was observed that tester parents typically had the lowest mean performance in a variety of traits, whereas line parents generally contributed more variance than testers. For example, the hybrids tended to outperform both parents for the majority of traits (indicating mid-parent heterosis), and the lines' mean leaf area was higher on average than the testers'. These patterns are in line with the hypothesis that superior trait values can be passed down from carefully chosen elite lines, and that crossing them with testers can result in transgressive segregants that are superior to their parents.

The ability to combine general and specific skills

Estimates of specific combining ability (SCA) for each hybrid cross and general combining ability (GCA) for each parent were obtained from the Line × Tester analysis. Overall, non-additive gene action predominated: the ratio of SCA/GCA exceeded 1, and for most traits, the SCA variance was larger than the GCA variance. This suggests that while additive genetic variance (as measured by GCA) was comparatively smaller, dominance and epistatic interactions were important in the inheritance of those traits. There was an exception for the number of leaves per plant, where the difference between GCA and SCA was negligible and additive effects were more comparable. Given that traits controlled by non-additive gene effects can exhibit significant improvement in hybrids, these results suggest that heterosis breeding is a promising approach.

Even though SCA predominated overall, some parental lines had notable GCA effects. Specifically, two line genotypes—HZ-6 and HZ-9—proved to be excellent general combiners for a variety of traits. Line HZ-6 exhibited a strong positive GCA for head diameter and the highest positive GCA effects for internodal length and plant height. Alleles for taller, more vigorous plant growth and longer internodes (possibly contributing to plant architecture) are carried by HZ-6, the only line with a significantly positive GCA for plant height (GCA = +8.15*) and a highly significant positive GCA for internodal length (GCA = +1.67**). Larger head size (head diameter GCA = +1.43**), a crucial yield component, was also greatly influenced by HZ-6. Conversely, line HZ-9 had the highest GCA for seed yield per plant and a noteworthy positive GCA for internode length and head diameter. For instance, HZ-9 passed on genes for greater achene yield and larger capitulum size to its offspring, as evidenced by its GCA of +1.84** for seed yield and +1.20** for head diameter. Additionally, line HZ-8 showed a strong GCA for seed yield (+1.81**) and might be regarded as a good productivity trait combiner. HZ-7, on the other hand, was a poorer general combiner than HZ-6, HZ-8, and HZ-9, as evidenced by the generally lower or even negative GCA values for many traits (e.g., GCA for plant height 5.07, for seed yield +0.80, both non-significant). The GCA effects were less noticeable among testers. While PBG-2 had a negative GCA for leaf area (indicating that it tended to reduce leaf size in hybrids), tester PBG-1 displayed a positive GCA for plant height and leaf area. As might be expected given that the lines were selected based on their elite qualities, the testers' contributions were generally less consistent than those of the lines.

Certain crosses that performed exceptionally (beyond what would be expected from the parents' GCAs) were identified by the specific combining ability results. The importance of non-additive interactions was supported by the statistical significance of many SCA effects. Notably, strong SCA in desired directions was frequently observed in hybrids involving the top general combiners (HZ-6 and HZ-9). These particular line-tester combinations produced hybrids with significantly larger heads than anticipated, as evidenced by the cross HZ-7 × PBG-1, which had one of the highest positive SCA effects for head diameter (+1.73**), and HZ-8 × PBG-2, which also displayed a large positive SCA for head diameter (+1.69**). On the other hand, for some traits, some crosses had significantly negative SCA effects, which meant that the hybrid's performance was lower than the parental mean. For example, HZ-8 × PBG-1 had a significantly negative SCA for stem diameter (–0.92), and HZ-6 × PBG-3 had a highly significant negative SCA for leaf area (–62.73). Negative SCA can be advantageous for traits where a reduction is desirable (e.g., plant height if aiming for shorter plants), but it is undesirable for traits where higher values are better (e.g., leaf area or stem thickness). However, the majority of the target traits in our study contributed to yield, with higher values being preferred.

A summary of the exceptional parent lines and hybrid combinations found through combining ability analysis is shown in Table 1. The best general combiners (high GCA) for several yield-related traits were determined to be HZ-6 and HZ-9. High SCA was shown by a number of hybrid combinations, which translated into better trait performance.

Table 1 presents a summary of the standout parent lines and hybrid combinations identified by combining ability analysis. HZ-6 and HZ-9 were confirmed as the best general combiners (high GCA) for multiple yield-related traits. Several hybrid combinations exhibited high SCA, translating into superior trait performance.

Table 1.

Notable sunflower genotypes identified by combining ability analysis. Stars indicate significance of GCA/SCA effects (* $p < 0.05$, ** $p < 0.01$).

Genotype (Role)	**Notable Effects and Traits**	**Description of Performance**
HZ-6 (Line)	+GCA for plant height*; +GCA for internode length**; +GCA for head diameter**.	Strong general combiner for taller plants, longer internodes, and larger heads.
HZ-9 (Line)	+GCA for head diameter**; +GCA for seed yield**; +GCA for internode length*.	Strong general combiner for yield (more seeds per head) and related traits.
HZ-6 × PBG-3 (Hybrid)	+SCA for head diameter (high mean performance); –SCA for leaf area**; –SCA for stem diameter**.	Hybrid with a **large head size**, though leaf area and stem thickness were lower than expected. Exhibited **high yield per head** in absolute terms (out-yielding all parents).
HZ-8 × PBG-1 (Hybrid)	+SCA for 100-seed weight (high mean seed size); +SCA for plant height (tallest plants); –SCA for head diameter*.	Hybrid with the **heaviest seeds and tall plants**, indicating vigorous growth; slightly smaller head size than expected.
HZ-8 × PBG-3 (Hybrid)	+SCA for head diameter** (largest head diameter observed); +SCA for leaf area (high mean leaf area)	Hybrid with **very large capitulum size** and broad leaves, contributing to yield potential.

(Note: GCA = general combining ability effect, SCA = specific combining ability effect. "+" indicates a positive effect (desirable for yield traits), "–" indicates a negative effect. Traits with non-significant GCA/SCA for these genotypes are not listed.)

As can be observed above, hybrid HZ-6 × PBG-3 generated one of the highest seed yields per plant in the trial (63.3 g seed per head, compared to a parental mean of ~57 g) by combining the strengths of its parents. Out of all the crosses, the hybrid HZ-8 × PBG-1 had the tallest plants (mean height ~174 cm) and the largest 100-seed weight (high seed mass). The largest sunflower heads (more than 20 cm in diameter) were produced by HZ-8 × PBG-3, which is a desirable trait for boosting yield. Various hybrid combinations performed exceptionally well in various traits, highlighting the importance of considering a variety of traits when choosing possible hybrids.

The hybrid vigour of heterosis

For important agronomic traits, a number of the F_1 hybrids showed significant heterosis over their parents. Negative heterosis, or decreased height, was actually preferred for plant height in order to prevent excessively tall plants; crosses HZ-7 × PBG-3 and HZ-9 × PBG-3 showed the most dwarfing heterosis, being about 13.8% shorter than their superior parent. Conversely, crosses such as HZ-6 × PBG-1 (+23.6% taller than the best parent) showed positive heterosis for plant height (hybrids taller than the taller parent), suggesting vigour in stem growth.

Numerous hybrids displayed heterotic increases in head diameter. Notably, the better-parent heterosis for head diameter was +27.2% for HZ-6 × PBG-3, +26.1% for HZ-8 × PBG-3, and +19.0% for HZ-8 × PBG-2. The hybrid heads were noticeably bigger than even the superior parent due to these substantial gains, which can directly result in a higher seed yield per head. In fact, the majority of hybrids with larger heads also produced more seeds per plant than their parents, indicating that head size heterosis and yield heterosis were related. Most crosses showed positive mid-parent heterosis in seed yield per head (achene yield per plant); all but one hybrid produced more than the average of its parents, and several even surpassed the yield of the superior parent. Crosses HZ-6 × PBG-1 and HZ-9 × PBG-1, for instance, demonstrated significant hybrid vigour in productivity with high better-parent heterosis for seed yield (+66.9% and +44.9%, respectively). The benefit of hybrid breeding for yield was confirmed by the F_1 hybrids' average production of more grain weight per plant compared to the parental inbreds.

Additionally, heterosis was assessed for characteristics such as 100-seed weight. It's interesting to note that a slight negative heterosis was prevalent in this case; many hybrids had 100-seed weights that were somewhat lower than those of their superior parent, perhaps as a result of an inverse relationship with seed number (more seeds but slightly smaller size). For example, a hybrid such as HZ-6 × PBG-2 showed a slightly better-parent heterosis of –2.4%, effectively maintaining seed size close to the parent, whereas the best parent for seed size might have had ~6.5 g per 100 seeds. If offset by a greater number of seeds per head, such negative or insignificant heterosis in seed weight need not be an issue. However, in certain crosses, leaf area showed significant positive heterosis, which is advantageous for photosynthetic capacity. Particularly large leaves were seen in crosses involving HZ-6; for example, HZ-6 × PBG-1 displayed +164.8% mid-parent heterosis for leaf area, suggesting that the hybrid's foliage was more than twice as large as the average of its parents. This implies that the genes governing leaf development interact in a complementary manner, which could result in more robust growth and increased yield capacity.

Overall, the results of the combining ability were supported by the heterosis analysis. In fact, the hybrids that our SCA analysis found to be exceptional (like HZ-6 × PBG-3 and HZ-8 × PBG-1) displayed better trait values than their parents. While some traits, such as stem diameter and internode length, displayed negative heterosis in some crosses, positive heterosis predominated in yield components (head size, seed number, and leaf area). The latter might indicate that some hybrids had shorter internodes or somewhat thinner stems than their parents, which could be trade-offs for allocating resources to seed production. Crucially, there was no discernible negative heterosis for yield per se; in most hybrids, the total seed yield per plant was higher than in the parents, even in cases where the 100-seed weight was lower. This suggests that hybrid combinations were able to increase sunflower productivity by effectively utilizing genetic vigour.

Discussion

The importance of hybrid breeding for sunflowers was reaffirmed by this study, which showed notable heterosis and combining ability variation in this crop. In our sunflower material, dominance and epistatic interactions appear to be important performance drivers, as evidenced by the prevalence of non-additive gene action (SCA > GCA for the majority of traits). Because hybrid varieties can capture those beneficial interactions that individual inbred parents cannot, such a genetic architecture is advantageous for heterosis exploitation. Our results are consistent with those of other researchers who found that non-additive variance predominates in sunflowers for traits related to yield. For example, in their sunflower line × tester analysis, Azad et al. (2016) found that non-additive genetic factors predominated for all traits (apart from days to maturity). Likewise, research in other crop contexts has observed that high heterosis traits frequently exhibit SCA variance greater than GCA variance, indicating that choosing the appropriate hybrid combination is more important than the average performance of the parents.

To guarantee consistently better offspring, it is still crucial to find parents with strong general combining ability. Lines HZ-6 and HZ-9 proved to be excellent general combiners in our experiment. For instance, HZ-6 carried advantageous alleles for vigour and sink capacity, as evidenced by the increased plant height, head size, and internode length in its hybrids. In crosses, HZ-9 was noteworthy for increasing head diameter and seed yield, indicating that it has genes for high seed production. These lines' high GCA may be the result of cumulative additive gene effects from earlier selection cycles. In order to widely transmit desired traits in a breeding program, breeders can use these lines as parent material. Our findings are in line with those of Nasreen et al. (2016), who also found that some inbred lines had significant GCA effects for characteristics such as head diameter and 1000-seed weight. It follows that in sunflower breeding, HZ-6 and HZ-9 can be utilized as important parental lines to create new hybrids or synthetics with higher potential yields. PBG-1 demonstrated some positive influence (for example, for plant height and leaf area) on the tester side, suggesting that it might be useful in particular crosses, even though the GCA effects were smaller.

The results of the specific combining ability analysis identified specific cross combinations that outperformed the expected general breeding values of the parents. This highlights the existence of distinct complementarity among specific genomes. Our study's most notable hybrids, including HZ-6 × PBG-3, HZ-8 × PBG-1, and HZ-8 × PBG-3, most likely use complementation for various trait complexes. For example, HZ-6 × PBG-3 produced a hybrid with exceptional head diameter and seed yield by crossing a high-GCA line (HZ-6) with a tester (PBG-3), which may carry alleles to further increase head size and yield. The superior performance of HZ-8 × PBG-1 in terms of seed weight and plant height points to an additive × additive interaction that results in overall vigour. Given the strong correlation between head size and seed yield, it is noteworthy that the hybrid HZ-8 × PBG-3 had the largest heads. This cross may be taking advantage of special genes from PBG-3 for robust growth and from HZ-8 for sink size. It's interesting to note that, despite HZ-9's high GCA, not all of the best hybrids included it. This shows that certain moderate-GCA parents can produce exceptional SCA with the right partner by matching certain traits (such as compatibility, flowering time, nicking, or specific gene complementation). Bhoite et al. (2018) made similar findings, highlighting the significance of testing a variety of cross combinations. They discovered that some sunflower hybrids had exceptional SCA even when one parent's GCA was unremarkable.

Our heterosis analysis offers verifiable proof of hybrid vigour and is consistent with the insights regarding combining ability. In terms of seed yield, many hybrids performed significantly better than their parents (20–60% higher than the superior parent in top crosses), which is practically significant for boosting output. In sunflower breeding programs, high heterosis for yield has been frequently reported; some studies have found that the best hybrids have yield gains of over 30% when compared to standard checks. In addition to yield per se, we also found heterosis for yield components that are easier to measure in small plots, such as head diameter and seed number, and that are suggestive of a hybrid's potential. The hybrids are taking advantage of dominance effects at several loci controlling these quantitative traits, as evidenced by the significant positive heterosis found in those traits in our study. Shorter hybrids with the same seed output may be agronomically superior; negative heterosis in traits such as plant height in some crosses may be advantageous if it aids in lodging resistance or harvest index optimization. In fact, our shortest hybrids (like HZ-7 × PBG-3) continued to produce competitive yields, indicating that productivity was not negatively impacted by plant height reduction. This is probably because resources were redirected toward seed development. Aiming for semi-dwarf sunflower hybrids that are less likely to lodge while maintaining a high yield, other researchers have observed this phenomenon (Deshmukh et al., 2016).

The outcomes of this experiment are extremely valuable from the standpoint of practical breeding. Since HZ-6 and HZ-9 are powerful combiners, a range of hybrids may be created using these lines. For example, crossing HZ-9 with various testers may regularly result in good offspring for traits like head size and yield. On the other hand, lines with low GCA (such as HZ-7 in our situation) may be removed from the breeding program or utilized exclusively for population enhancement instead of serving as hybrid parents. Further testing in multi-location trials is warranted for the particular crosses that performed exceptionally well, especially HZ-6 × PBG-3 and HZ-8 × PBG-1. They might be promoted as potential hybrids for release if their performance remains consistent across environments. One or more of these experimental hybrids might perform better than the current commercial sunflower varieties, which would be very beneficial to local farming. Furthermore, knowledge about heterosis can direct breeding strategy: in this situation, a hybrid breeding program (as opposed to creating open-pollinated varieties) is warranted for sunflower improvement because non-additive effects predominate. To create these crosses on a bigger scale, as is typical in the production of sunflower hybrid seeds, breeders might also look into creating synthetic varietal hybrids or employing cytoplasmic male sterility systems.

Our research also advances our knowledge of sunflower genetics by validating some established relationships (such as the importance of selecting parents from different backgrounds to maximize heterosis and the contribution of larger heads and greater leaf area to yield). Our parent lines were sufficiently genetically different to produce new gene combinations, as evidenced by the significant line × tester interactions found for every trait. This divergence is crucial because heterosis is typically restricted if lines are too closely related. In the future, adding even more varied germplasm (like exotic inbred lines or wild sunflowers) might boost heterosis even more. All of our lines and testers were already locally adapted, which probably helped explain the hybrids' generally good performance (no serious breakdown in any cross).

Nevertheless, one must strike a balance between diversity and the requirement for agronomically adapted material.

In conclusion, the findings clearly support the use of hybrid breeding in sunflowers in order to increase yield quickly. Promising hybrid candidates have been produced by combining high GCA lines (HZ-6, HZ-9) with careful crosses to take advantage of SCA. These results are in line with national goals to increase sunflower production in order to alleviate the scarcity of oilseeds. Similar tactics have been proposed in the literature, highlighting the fact that a successful crop improvement pathway involves first choosing parental lines with high GCA and then identifying hybrids with high SCA and heterosis (Khan et al., 2018; Ashraf et al., 2024). Our contribution is to identify the genotypes that meet these requirements in a local breeding program.

Conclusion

Through a line × tester analysis, this study offered important insights into the genetic control of yield and its constituent parts in sunflower. For most traits, non-additive gene action predominates, suggesting that taking advantage of heterosis is a practical and successful method of improving sunflowers. Our study confirmed the existence of significant heterotic gains by showing that hybrid combinations consistently outperformed their parent lines for important traits. Two parent lines, HZ-6 and HZ-9, were found to have exceptional general combining ability; because of their capacity to favourably influence a variety of yield-related traits in hybrids, these lines can be regarded as cornerstone breeding lines. Furthermore, certain hybrids, like HZ-6 × PBG-3 and HZ-8 × PBG-1, showed remarkable performance and are therefore excellent prospects for becoming commercial hybrid varieties. Both hybrids use non-additive interactions to improve upon current genotypes; HZ-6 × PBG-3, in particular, combined large head size and robust yield, while HZ-8 × PBG-1 produced heavy seeds and vigorous growth.

The results demonstrate that, in contrast to conventional open-pollinated variety development, a hybrid breeding program can dramatically increase sunflower yield in a brief amount of time. Breeders can optimize genetic gain by using high-GCA parents to create new inbred lines, which are then crossed to create hybrids with high SCA. To verify their yield advantage and environmental stability, the promising crosses from this study will undergo additional testing in larger trials. They might directly boost sunflower production if they are successful. In Pakistan, where boosting domestic edible oil production is a top priority, this is especially pertinent. Adoption of improved sunflower hybrids could increase farmer incomes and lessen the nation's reliance on imported oil by allowing for two cropping seasons annually.

To sum up, the thesis-based study confirmed the effectiveness of line × tester analysis in identifying sunflower germplasm's additive and non-additive genetic potential. It gave sunflower breeding a clear path forward, emphasizing the creation of hybrids through the use of the discovered combiners and cross combinations. In addition to adding to the global body of research on sunflowers, the improved knowledge of heterosis and combining ability gained from this work will help plant breeders develop strategies for producing next-generation sunflower hybrids with improved agronomic traits, higher yields, and greater economic value.

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