

DECIPHERING VARIABILITY AND HETEROSIS IN BARLEY FOR SUSTAINABLE YIELD POTENTIAL

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Abstract. This study underscores the critical role of genetic variability and heterosis in improving the yield potential of barley (*Hordeum vulgare* L.). For the majority of traits, there were notable changes between the parents, hybrids, and their interactions, demonstrating the significant genetic diversity and efficacy of the selected breeding strategy. For parameters including plant height, spike length, grains per spike, tillers per plant, 1000-grain weight, and grain yield per plant, general combining ability (GCA) variants were less than specific combining ability (SCA) variances, suggesting the dominance types of gene action. Among parents, L7 is a promising genotype for higher grain yield, while L5 and L3 showed strengths in other yield-related traits. Significant SCA effects, however, highlighted the importance of non-additive gene action for several characteristics and raised the possibility of heterosis exploitation. Hybrids like L7×T4 and L5×T3, which exhibited superior performance in key traits, demonstrate the potential for developing high-yielding barley varieties through heterosis, whereas line L3, L7 and tester T3 showed the strongest positive GCA effects for plant height and spike length, respectively. The findings underscore the significance of dominance gene activities in barley breeding and show that careful parent selection and hybridization can result in superior hybrids with higher yield potential.

Keywords: *additive, crosses, GCA, gene, traits, genetics*

Introduction

Barley (*Hordeum vulgare* L.) is one of the oldest and most important cereal crops cultivated globally. It has played a pivotal role in human nutrition, agriculture, and industry for thousands of years. As a staple crop, barley is not only a significant source of food and feed but also an essential ingredient in the brewing and malting industries. Its adaptability to diverse climatic conditions and soil types makes it a valuable crop for both temperate and semi-arid regions. The economic importance of barley is underscored by its use in various products, including malt for beer production, animal

feed, and even health foods (Sharma et al., 2002; Yu et al., 2024). Given the increasing global population and the need for sustainable agricultural practices, improving barley yield and quality is crucial for meeting future food security and economic demands (Amer et al., 2012).

Despite its significance, barley production faces several challenges that impact yield and quality. Climate change, pest and disease pressures, and soil fertility issues are major factors influencing barley cultivation (Prakash et al., 2005; Pawar and Singh, 2013). The increasing variability in weather patterns, including droughts and floods, has had a direct impact on barley yield and quality. Additionally, diseases such as barley yellow dwarf virus and pests like aphids can severely affect crop performance. To address these challenges, breeders and researchers focus on enhancing barley's resilience and productivity through genetic improvement. Understanding the genetic basis of yield and related traits is essential for developing barley varieties that can withstand adverse conditions while maintaining high productivity (Potla et al., 2013; Bornare et al., 2014; Baloch et al., 2024)

The discovery and modification of genes linked to important agronomic properties is a necessary step in the genetic improvement of barley. Overall crop performance is mostly dependent on yield and yield-related parameters, including plant height, spike length, grains per spike, tillers per plant, 1000-grain weight, and grain yield per plant (Adriana et al., 2015; Patial et al., 2016). These traits are influenced by both additive and non-additive gene actions, which can be assessed through various genetic analyses. Additive gene action refers to the cumulative effect of individual genes on a trait, while non-additive gene action involves interactions between genes that result in different trait expressions in hybrids compared to their parents. Understanding the relative contributions of these gene actions helps in designing effective breeding strategies (Tokhetova et al., 2022; Kalyar et al., 2024; Mushtaq et al., 2024).

The line \times tester mating design is a well-established method for evaluating the combining ability of parental lines in breeding programs (Ram and Shekawat, 2017; Lal, 2018). This approach allows for the assessment of general combining ability (GCA) and specific combining ability (SCA) effects, which provide insights into the additive and non-additive genetic contributions to trait inheritance. GCA effects reflect the average performance of a parent across different crosses and are indicative of its overall genetic potential. In contrast, SCA effects highlight the performance of specific line \times tester combinations, revealing the presence of interaction effects between parental lines (Sallam et al., 2018; Swati et al., 2019). By analyzing GCA and SCA effects, breeders can identify the most promising lines and testers for developing high-yielding and resilient barley varieties. This method also aids in understanding the genetic mechanisms underlying trait expression and guide the selection of parent lines with desirable attributes.

Previous studies on barley combining ability have provided valuable insights into the genetic basis of key traits (Kumari et al., 2020; Katiyar et al., 2021). Research has demonstrated that both additive and non-additive gene actions contribute to the inheritance of traits such as plant height, spike length, and grain yield. For instance, studies have shown that plant height and spike length are often controlled by additive gene effects, while grains per spike and tillers per plant may involve significant non-additive interactions (Pesaraklu et al., 2016). Research on combining ability in barley has also highlighted the importance of selecting appropriate parental lines for breeding programs. Lines with high GCA effects for yield-related traits are often chosen for

developing hybrids with improved performance. Additionally, the identification of crosses with favorable SCA effects can lead to the development of superior hybrids with enhanced productivity (Verma et al., 2021).

The hybrid crossing system in barley is a crucial method for commercial production, aimed at enhancing desirable traits such as yield, disease resistance, and environmental stress tolerance. The most commonly used crossing systems are two-way crosses and three-way crosses (Thomas et al., 2019). In a two-way cross, two genetically distinct parental lines with complementary traits are crossed to produce hybrid progeny. In a three-way cross, an additional parent is introduced, often combining the strengths of three different lines to optimize traits further. These crosses produce F₁ hybrid seeds, which exhibit heterosis (hybrid vigor), leading to superior performance in terms of growth rate, yield, and resilience compared to the parental lines (Mühleisen et al., 2013; Ahokas, 2018). This hybrid system is vital for commercial barley production because it maximizes the genetic potential of the crop, leading to increased productivity and improved agronomic characteristics. Additionally, the use of hybrid seeds ensures uniformity and consistency in crop quality. The hybrid crossing system is a key strategy in meeting the growing global demand for barley, especially for brewing, animal feed, and food industries (Jolliffe et al., 2023).

Using a line \times tester mating strategy, the objective of this study was to assess the combining ability of different barley lines and testers for important yield-related variables. The particular goals of the study were estimating the effects of GCA and SCA on plant height, spike length, grains per spike, tillers per plant, 1000-grain weight, and yield per plant, to choose the lines and testers with the best potential depending on how well they combine. To determine the nature of gene action (additive vs. non-additive) controlling these traits. To provide recommendations for breeding strategies that can enhance barley yield and related traits.

By addressing these objectives, the study seeks to contribute to the advancement of barley breeding programs and the development of high-yielding varieties that can meet the demands of modern agriculture. By identifying lines and testers with favorable GCA and SCA effects, the study will aid in the selection of superior parental material for breeding programs (Bishnoi et al., 2022). The results will also help in understanding the relative contributions of additive and non-additive gene actions, guiding the development of effective breeding strategies.

Materials and methods

The study utilized 53 barley genotypes, (8 lines and 5 testers and 40 their F₁ generations), all of which were two-rowed. The parental genotypes were chosen based on their distinct genetic backgrounds and their potential to exhibit variability in the traits of interest. In this study 5 testers likely, T1 (TJ-70), T2 (Jyoti), T3 (Sadabhar), T4 (Frontier-87) and T5 (Sanober-96), While the 8 lines L1 (Haider-93), L2 (Talbina-21), L3 (Jau-21), L4 (Peral-21), L5 (Sultan-17), L6 (Rakhshan-10), L7 (Jau-17) and L8 (Neelum) were used. The lines and testers were selected from existing germplasm collections to ensure a broad representation of genetic diversity. Forty hybrids (F₁ generations) were produced during the 2021-2022 growing season by crossing these genotypes using a line \times tester mating scheme. In the Rabi season of 2022–23, these hybrids were assessed in a Randomized Complete Block Design (RCBD) with three replications at the Department of Plant Breeding and Genetics, The Islamia University

of Bahawalpur, Pakistan alongside the parent genotypes. Each test genotype was sown in rows of 2.0 meters in length, with a plant-to-plant spacing of 15 cm and a row-to-row spacing of 30 cm. Standard agronomic practices were followed for crop management. Irrigation was applied at critical growth stages, including early tillering, booting, and grain filling. Weeding was performed as needed. The evaluation focused on combining ability and gene action for six traits: plant height (cm), spike length (cm), grains per spike, tillers per plant, 1000-grain weight (g), and grain yield per plant (g). ANOVA was conducted to determine the significance of differences among lines, testers, and their crosses for all measured traits. The analysis was performed using the Duncan's Multiple Range (DMR) test to separate mean values at $p \leq 0.05$ (Duncan, 1955). Combining ability analysis was carried out to estimate general combining ability (GCA) and specific combining ability (SCA) effects. GCA effects were estimated based on the performance of each line and tester across all crosses. SCA effects were calculated for each cross, reflecting the deviation from the expected performance based on GCA effects. The combining ability analysis followed the method outlined by Kempthorne (1957).

Results and discussion

The analysis of variance for combining ability (*Table 1*) revealed significant differences among parents, hybrids, and lines \times testers for most of the traits studied. Specifically, the parents exhibited significant variation for all traits, with the exception of spike length, indicating the presence of substantial genetic diversity. The hybrids also showed significant variation for all traits, suggesting the effectiveness of the line \times tester mating design in generating variability. The comparison between parents and hybrids demonstrated highly significant differences for all traits, confirming the superiority of hybrids over their parents in terms of yield-related attributes (Bornare et al., 2014; Lal, 2018; Swati et al., 2019).

Table 1. Analysis of variance for combining ability for yield and yield related traits of barley

Source of variation	Df	Plant height (cm)	Spike length (cm)	Grains per spike	Tillers per plant	1000-grain weight (g)	Grain yield per plant (g)
Parents	12	142.85*	1.29*	749.12**	2.81*	104.15**	2.73**
Hybrids	39	202.84**	2.07*	411.78**	34.98*	237.14**	11.21*
Parents vs. hybrids	1	1.79	2.27**	1401.25**	49.32**	3361.84**	130.14**
Lines	7	470.92**	1.64	870.45*	78.63**	584.22*	6.24
Testers	54	389.41	4.12*	320.39	49.52	290.71	28.32*
Lines \times testers	28	107.34**	1.92**	305.47**	21.88*	147.65*	9.74*
Error	52	8.37	0.27	5.62	3.22	18.45	0.42
GCA effects		25.04	0.09	23.07	3.17	23.35	0.61
SCA effects		48.62	0.81	151.89	9.15	62.39	4.58
GCA/SCA		0.497	0.087	0.148	0.351	0.358	0.119

ns, *, ** non-significant, significant at 5% and 1% level, respectively

To ascertain the type of gene activity governing these qualities, the variances of the general combining ability (GCA) and the specific combining ability (SCA) were also calculated. For plant height, spike length, grains per spike, tillers per plant, 1000-grain weight, and grain yield per plant, the GCA variations were greater than the SCA

variances, suggesting that additive gene action is primarily responsible for determining these attributes. For every characteristic, the GCA/SCA ratio was smaller than 1, indicating that additive gene action predominates (Sharma et al., 2002; El-Bawab, 2003; Pawar and Singh, 2013; Verma et al., 2021). Plant height, spike length, grains per spike, tillers per plant, 1000-grain weight, and grain yield per plant show substantial variations between parents and hybrids. These observations imply that these qualities are governed by genetic variables that may be efficiently altered by selective breeding. The significant GCA effects for most traits indicate that additive genetic variance plays a crucial role, making these traits amenable to improvement through selection. The higher GCA variances relative to SCA variances and the GCA/SCA ratio below 1 for all traits confirm the predominance of additive gene action (Sharma et al., 2002; Singh et al., 2002; Adriana et al., 2015; Ram and Shekawat, 2017).

Certain variables, such as spike length and grains per spike, show strong SCA effects, indicating that non-additive gene activity also plays a role in the transmission of these features. This emphasizes how barley breeding efforts may be able to take advantage of heterosis. Both additive and non-additive genetic effects are present when lines, testers, and their interactions differ significantly from one another; the latter is essential to hybrid performance (Prakash et al., 2005; Sallam et al., 2018; Ijaz et al., 2023). These findings imply that the inheritance of important yield-related features in barley is influenced by both additive and non-additive gene activities, with additive effects predominating. Thus, choosing parents with strong GCA effects may result in the creation of superior barley hybrids with higher potential yields. The results further highlight the significance of hybrid breeding approaches that take use of additive and non-additive gene effects in order to optimize barley production and associated attributes (Swati et al., 2019; Verma et al., 2021).

Performance of lines and testers

The mean performance of the barley lines and testers for yield and yield-related traits is presented in *Table 2*. Among the lines, L5 exhibited the greatest plant height (101.2 cm), while L4 had the shortest height (76.5 cm). Spike length varied across the lines, with L1 having the longest spike (9.0 cm) and L8 the shortest (7.4 cm). Regarding grains per spike, L3 had the highest number of grains (74), while L5 had the lowest (22). For tillers per plant, L8 recorded the highest number (14.7), whereas L4 had the fewest (11.8). The 1000-grain weight ranged from 57.3 g in L8 to 41.1 g in L6. In terms of grain yield per plant, L7 performed the best with 11.2 g, and L2 the lowest with 7.9 g. Among the testers, T3 stood out with the greatest plant height (102.4 cm) and grains per spike (62). T2 had the shortest plant height (85.8 cm) and the fewest grains per spike (20). T5 showed the lowest 1000-grain weight (35.6 g) and grain yield per plant (7.6 g), while T4 had the highest grain yield per plant (10.5 g).

The DMR test results highlight significant differences in the performance of barley lines for various traits (*Table 2*). L5 (101.2 cm) was the tallest plant, significantly outperforming the other lines in plant height, while L1, L2, L3, T3, T4, and T5 had similar heights around 80-85 cm, falling into the same statistical group. L4 (76.5 cm) and L8 (77.3 cm) were notably shorter. In terms of spike length, L1 (9.0 cm), L5 (8.8 cm), L6 (8.7 cm), and L7 (8.6 cm) showed similar results, all falling into group "a." L2 (7.9 cm) and L4 (7.8 cm) had slightly shorter spikes, while T2 (6.5 cm) had the shortest, significantly different from the rest. For grains per spike, L3 (74 grains) outperformed the other lines, falling into group "a," while L4 (64 grains) and T4 (56 grains) also performed

better than the rest. T2 (20 grains) and L5 (22 grains) had significantly fewer grains, placing them in group “c,” and the other lines such as L1, L7, and T3 had intermediate results. When it comes to tillers per plant, L5 (14.2 tillers) had the highest number and belonged to group “a,” while L1, L2, L3, T1, T4, and T5 showed no significant differences, all falling into group “ab.” L7 (12.4 tillers) and L6 (12.8 tillers) had slightly lower tiller counts. For 1000-grain weight, L7 (54.1 g), L5 (50.9 g), and T1 (56.2 g) were the highest, while T2 (54.1 g) and L6 (41.1 g) showed lower weights. L8 (57.3 g) also had a relatively high 1000-grain weight, though results varied among the lines. Finally, L7 (11.2 g) had the highest grain yield per plant, significantly outperforming the other lines, while L4 (9.9 g) and T3 (9.4 g) had moderately high yields. The remaining lines, including L1 (8.4 g), L2 (7.9 g), L5 (8.7 g), and L8 (8.5 g), had similar grain yields, and T2 (7.0 g) had the lowest yield, placing it in the lowest statistical group. Overall, the DMR test results suggest that L7 is a promising genotype for higher grain yield, while L5 and L3 show strengths in other yield-related traits.

Table 2. Mean performances of lines and testers for yield and yield related traits of barley

Parents	Plant height (cm)	Spike length (cm)	Grains per spike	Tillers per plant	1000-grain weight (g)	Grain yield per plant (g)
L1	82.1c	9a	36b	13.8a	47.3b	8.4bc
L2	85.2c	7.9b	27c	13.2a	44.7bc	7.9c
L3	83.8c	8.5	74a	13.3a	41.2bc	8.1bc
L4	76.5d	7.8b	64a	11.8c	42.8bc	9.9b
L5	101.2a	8.8a	22c	14.2a	50.9a	8.7bc
L6	93.6b	8.7a	28c	12.8ab	41.1bc	8.7bc
L7	94.7b	8.6a	32b	12.4ab	54.1a	11.2a
L8	77.3d	7.4b	26c	14.7a	57.3a	8.5bc
T1	82.8c	8a	24c	12.3ab	56.2a	8.6bc
T2	85.8c	6.5bc	20c	11.2c	54.1a	7c
T3	102.4a	6.8bc	62a	14.3a	56a	9.4b
T4	83.1c	7.3b	56a	13.2a	45.2b	10.5ab
T5	86.7c	7.7b	58a	13.8a	35.6c	7.6c
SD ±	5.25	0.95	13.10	1.41	5.75	1.12

The analysis of mean performances among the barley lines and testers reveals significant variation across the studied traits. The observed differences in plant height, spike length, grains per spike, and other yield-related traits among the lines and testers highlight the genetic diversity within the parent material (Amer et al., 2012; Bornare et al., 2014; Ram and Shekawat, 2017). The notable performance of L7 for grain yield per plant suggests that it is a promising line for breeding programs aimed at improving yield. Similarly, the high number of grains per spike observed in L3 indicates its potential for contributing to increased grain production (Swati et al., 2019; Kumari et al., 2020; Fatemi et al., 2023).

The testers also displayed considerable variability, with T3 showing superior performance in both plant height and grains per spike. The high 1000-grain weight and grain yield per plant observed in T4 suggest that it could be an effective parent in hybrid combinations aimed at enhancing these traits. These findings underscore the importance

of selecting parents with desirable traits for use in hybridization programs. The significant variation observed in key yield components such as grains per spike, tillers per plant, and grain yield per plant suggests that these traits could be effectively improved through targeted breeding strategies (Lal, 2018; Sallam et al., 2018). The performance of the lines and testers indicates the potential for developing high-yielding barley hybrids by combining the strengths of different parent lines (Amer et al., 2012).

General combining ability (GCA) effects

As shown in *Table 3*, the estimations of general combining ability (GCA) impacts for barley lines and testers show clear differences in yield and yield-related variables. L3 showed the strongest positive GCA effects for both spike length (0.62) and plant height (8.60) among all the lines, indicating that it might be a donor for both characteristics. In contrast, L6 displayed the most substantial negative GCA effects across several traits, including plant height (-9.05) and grain yield per plant (-1.25), indicating its potential to contribute to the improvement of these characteristics through breeding. While lines L4 and L8 exhibited positive GCA effects for tillers per plant (5.85 and 0.31, respectively), lines L2 and L5 showed substantial positive effects for grain yield per plant (0.97 g and 7.95 g, respectively). T3 had the most positive GCA impact (6.75) for plant height among the tests, whereas T5 displayed the greatest negative effect (-7.52) for 1000-grain weight. T4 had favorable GCA effects for spike length (0.43) and grain production per plant (0.79), indicating its potential for enhancing these characteristics. T2 had significant negative GCA effects for plant height (-1.50) and grain yield per plant (-0.37).

Table 3. Estimates of GCA effects for lines and testers for yield and yield related traits of barley

Parents	Plant height (cm)	Spike length (cm)	Grains per spike	Tillers per plant	1000-grain weight (g)	Grain yield per plant (g)
L1	-3.10**	-0.18ns	-5.67*	0.72ns	5.38*	-0.18ns
L2	1.45*	-0.43*	-3.80**	5.85**	-0.23ns	0.97**
L3	8.60**	0.62**	12.72**	-1.58*	-2.74**	-0.3ns
L4	2.80*	0.07ns	16.98*	0.21ns	-4.30**	0.3ns
L5	7.33**	-0.53**	-7.12**	0.52ns	7.95**	-0.42*
L6	-9.05**	0.31*	-4.21**	-3.78**	-15.12*	-1.25*
L7	-9.72**	-0.23ns	-3.63**	-2.04**	0.95	-0.43**
L8	1.93**	0.31*	-5.50**	0.31ns	8.21*	1.24**
SE ±	0.66	0.13	0.53	0.48	1.19	0.19
T1	-6.35**	0.43**	-4.60*	1.34**	0.25ns	1.85**
T2	-1.50**	-0.28*	-4.35**	1.42**	2.55*	-0.37**
T3	6.75**	-0.56**	1.15*	0.72ns	2.54*	-0.89**
T4	2.50**	-0.28*	6.18**	-0.65ns	2.02*	0.79*
T5	-1.25**	0.64**	1.50**	-2.78*	-7.52**	-1.40**
SE ±	0.47	0.12	0.37	0.35	0.89	0.13

ns, *, ** non-significant, significant at 5% and 1% level, respectively

The analysis of GCA effects reveals that certain lines and testers have a clear potential to enhance specific traits in barley breeding programs. Line L3, with its

positive GCA effects on plant height and spike length, can be leveraged to increase the size and structural attributes of barley plants. However, its negative effects on grain yield highlight a trade-off that needs to be managed in breeding strategies. On the other hand, Line L6, which consistently shows negative GCA effects across multiple traits, might be valuable in breeding programs aimed at reducing undesirable characteristics (Ram and Shekawat, 2017; Lal, 2018; Victoria et al., 2023). The testers also demonstrated variability in their GCA effects. T3's positive impact on plant height suggests its suitability for breeding programs focused on taller barley plants. In contrast, T5's negative effect on 1000-grain weight could indicate its role in reducing grain size, which may be undesirable for some breeding objectives (Adriana et al., 2015; Patial et al., 2016). Notably, T4's positive effects on grain yield and spike length suggest its potential as a valuable contributor to enhancing these traits in barley populations. The distinct GCA effects observed across lines and testers underscore the importance of selecting appropriate parental material for achieving specific breeding goals. The variability in GCA effects can guide the selection of parent lines and testers to maximize desirable traits and achieve balanced improvements in barley yield and related characteristics (Potla et al., 2013; Bornare et al., 2014).

Specific combining ability (SCA) effects

In this study, *Table 4* presents the significant specific combining ability (SCA) effects and mean values for various barley crosses. The crosses L5×T3, L3×T4, and L7×T3 showed notably negative SCA effects for plant height, with values of -11.45, -10.72, and -8.05, respectively, and mean heights of 86, 74.8, and 69.2 (*Table 5*). These crosses demonstrate a potential for shorter plant stature, which could be advantageous in certain breeding scenarios. For spike length, crosses L7×T4 and L3×T3 exhibited positive SCA effects of 2.20 and 0.88, respectively, with mean spike lengths of 10.7 and 9.9, suggesting their potential to enhance this trait.

In terms of grains per spike, the cross L5×T3 had the highest positive SCA effect of 29.88 grains, with a mean value of 80.5 grains per spike, indicating its strong potential for increasing grain number. The cross L7×T4 also showed significant improvement with an SCA effect of 25.67 grains and a mean of 80.3 grains. Regarding tillers per plant, L7×T4 and L7×T3 were the most significant, with SCA effects of 6.40 and 6.15 tillers and mean values of 24.5 and 21, respectively.

For 1000-grain weight, the cross L3×T3 showed the highest positive SCA effect of 13.20, with a mean value of 75.2, indicating its potential to improve grain size. L5×T4 and L5×T3 also demonstrated notable positive SCA effects of 7.55 and 7.40, respectively. In grain yield per plant, L5×T3 achieved the highest SCA effect of 4.80, with a mean yield of 15.8 per plant, suggesting its strong potential for increasing yield. L7×T4 and L7×T3 also displayed significant positive effects with SCA values of 4.02 and 3.90, respectively.

The analysis of SCA effects highlights several promising barley crosses with significant impacts on key yield and yield-related traits. The crosses L5×T3, L3×T4, and L7×T3, despite their negative SCA effects on plant height, demonstrate considerable potential for reducing plant stature, which may be desirable for certain agronomic practices. The positive SCA effects observed in L7×T4 and L3×T3 for spike length suggest their utility in improving spike characteristics, potentially leading to better overall plant architecture and productivity.

Table 4. SCA effects of 40 crosses for yield and yield related traits of barley

Crosses	PH	SL	GPS	TPP	TGW	GYP
L1 × T1	-1.52ns	-0.84*	0.61ns	-1.27ns	1.21ns	-1.69ns
L1 × T2	0.93ns	0.74ns	0ns	2.37*	0.27ns	1.14ns
L1 × T3	2.73**	-0.55ns	0.61ns	0.34ns	0.74ns	1.36ns
L1 × T4	-2.14ns	0.66ns	-1.22ns	-1.44ns	-2.23*	-0.82ns
L1 × T5	-1.51ns	0.31*	-0.71ns	-0.28ns	0.62ns	-0.69ns
L2 × T1	-3.34**	-0.51ns	0.78ns	0.37ns	-0.45ns	1.14ns
L2 × T2	2.49**	0.2ns	1.48ns	2.35*	-1.92*	0.36ns
L2 × T3	2.37**	-0.59ns	-1.55ns	-2.43*	1.75ns	-0.82ns
L2 × T4	2.33**	0.42*	-1.76*	-1.27ns	-0.79ns	-0.19ns
L2 × T5	0.79ns	-0.26ns	1.63ns	-0.64ns	-0.45ns	1.64ns
L3 × T1	-1.7*	0.48*	1.03ns	2.35**	1.07ns	-1.14ns
L3 × T2	-1.42s	-1.34**	-0.9ns	-1.44ns	0.17ns	-0.32ns
L3 × T3	-3.25**	0.88**	0.24ns	-1.77ns	13.20**	1.06ns
L3 × T4	-10.72**	0.65*	12.65**	3.35**	-3.03**	2.98**
L3 × T5	-0.43ns	-0.68ns	-0.37ns	-0.13ns	-0.98ns	-2.11ns
L4 × T1	5.74**	-1.09**	-1.97*	-2.15*	1.49ns	-1.89ns
L4 × T2	1.36ns	-1.05**	2.1*	2.06**	2.52**	2.03**
L4 × T3	3.66**	0.07ns	0.48ns	-0.78ns	0.51ns	1.76ns
L4 × T4	-2.63**	-0.34ns	-1.13ns	-1.13ns	1.44ns	-0.41ns
L4 × T5	-2.39**	0.7ns	-0.73ns	-0.14ns	-2.02*	-1.97ns
L5 × T1	1.36ns	-0.43ns	0.8ns	2.05*	-1.46ns	0.63ns
L5 × T2	-0.6ns	0.07ns	-1ns	-1.33ns	0.15ns	0.48ns
L5 × T3	-11.45**	0.81**	29.88**	-0.34ns	7.40**	4.80**
L5 × T4	-7.95**	0.65ns	3.30**	3.15**	7.55**	0.68ns
L5 × T5	0.1ns	-0.3ns	1.38ns	2.87**	0.07ns	-1.3ns
L6 × T1	0.3ns	-0.43ns	1.57ns	-1.07ns	0.66ns	0.57ns
L6 × T2	-0.24ns	-0.34ns	-2.37**	-2.51*	1.62ns	2.05*
L6 × T3	-0.16ns	0.57ns	-0.63ns	0.7ns	-0.83ns	-1.72ns
L6 × T4	1.14ns	-0.39ns	1.43ns	2.84**	-1.46ns	0.57ns
L6 × T5	0.31ns	0.16ns	-0.66ns	-0.64ns	0.15ns	-1.3ns
L7 × T1	-0.75ns	-0.34ns	0.86ns	-0.87ns	-0.86ns	1.29ns
L7 × T2	-0.7ns	0.57ns	0.23ns	2.05*	1.34ns	-0.56ns
L7 × T3	-8.05**	-0.43ns	0.62ns	6.15**	-0.98ns	3.90**
L7 × T4	0.53ns	2.20**	25.67**	6.40**	6.70**	4.02**
L7 × T5	-1.29ns	-0.01ns	-0.6ns	-1.33ns	-0.63ns	-1.72ns
L8 × T1	-2.05*	0.24ns	-0.24ns	-0.34ns	0.67ns	0.57ns
L8 × T2	-3.34**	0.61ns	-0.71ns	0.88ns	-0.6ns	-0.69ns
L8 × T3	2.49**	-0.84*	0.78ns	-0.37ns	0.12ns	-0.47ns
L8 × T4	2.37**	0.16ns	1.48ns	-0.16ns	-0.19ns	0.57ns
L8 × T5	-0.16ns	-0.34ns	1.43ns	0.7ns	-0.98ns	-0.66ns

ns, *, ** non-significant, significant at 5% and 1% level, respectively. Plant height (PH), spike length (SL), grains per spike (GPS), tillers per plant (TPP), 1000-grain weight (TGW), and grain yield per plant (GYP)

Table 5. Mean performances of 40 crosses for yield and yield related traits of barley

Crosses	PH	SL	GPS	TPP	TGW	GYP
L1 × T1	90b	8.9c	52.3c	19c	70.4b	14.5b
L1 × T2	88c	8.7c	51.3c	17e	69.3c	13.2c
L1 × T3	92b	9.2ab	50.2c	20bc	71.5b	13.9c
L1 × T4	88c	9.3ab	52.3c	19c	68.8c	14.5b
L1 × T5	88c	7.8d	51.4c	17e	66.4c	14.2b
L2 × T1	89c	7.5d	52.1c	17e	67.8c	14.6b
L2 × T2	89c	8.4c	51.3c	19c	71.9b	13.5c
L2 × T3	98b	8.3c	50.3d	19c	72.9b	13.6c
L2 × T4	92b	9.4ab	51.3c	17e	69.4c	14.8b
L2 × T5	101a	9.5ab	52.4c	15de	68.3c	13.2c
L3 × T1	97b	9.1ab	49.8d	17e	68.2c	14.3b
L3 × T2	95b	8.9c	50.7c	18d	65c	14.1b
L3 × T3	91b	9.9b	48.5d	18d	75.2a	13.7c
L3 × T4	74.8d	10.3a	62.5b	20.5ab	71b	15.3a
L3 × T5	89c	8.8c	52.6c	18d	72b	13.8c
L4 × T1	90b	8.6c	51.2c	17e	70b	13.9c
L4 × T2	92b	7.6d	51.3c	16de	71b	13.6c
L4 × T3	88c	7.5d	50.3d	15de	69c	13.6c
L4 × T4	89c	9.2ab	51.3c	17e	65c	14.8b
L4 × T5	92b	8.3c	49.8d	16de	66c	13.2c
L5 × T1	102a	8.2c	50.7c	18d	67c	14.3b
L5 × T2	100 a	8.4c	50.2c	19c	68c	14.1b
L5 × T3	86cd	9.6b	80.5a	18d	76.3a	15.8a
L5 × T4	64e	9.4ab	53.5c	24.8a	78.8a	13.4c
L5 × T5	101a	9.3ab	52.1c	17e	69c	12.9cd
L6 × T1	98b	9.1ab	51.3c	18d	70b	13.1c
L6 × T2	95b	9ab	50.3d	19c	71b	12.8cd
L6 × T3	88c	8.9c	51.3c	15de	68c	13.8c
L6 × T4	94b	7.8d	49.8d	17e	67c	12.8cd
L6 × T5	96b	7.9d	50.7c	16de	68c	14.1b
L7 × T1	98b	8.3c	48.5d	18d	69c	14.5b
L7 × T2	95b	9.1ab	50.3d	19c	67c	13.7
L7 × T3	69.2de	8.2c	51.3c	21ab	68	15.6a
L7 × T4	98b	10.7a	80.3a	24.5a	77.9a	16.9a
L7 × T5	95b	8.1c	49.8d	17e	68c	12.9cd
L8 × T1	88c	9.4ab	50.7c	18d	67c	13.1c
L8 × T2	88c	7.8d	50.3d	17e	68c	14.5b
L8 × T3	94b	7.9d	51.3c	18d	69c	14.8b
L8 × T4	96b	8.5c	50.7c	19c	72b	12.8cd
L8 × T5	99b	8.5c	49.6d	19c	71b	13.9c
<i>SD</i> ±	<i>11.30</i>	<i>0.75</i>	<i>9.94</i>	<i>2.04</i>	<i>3.11</i>	<i>0.88</i>

Plant height (PH), spike length (SL), grains per spike (GPS), tillers per plant (TPP), 1000-grain weight (TGW), and grain yield per plant (GYP)

For grains per spike, the crosses L5×T3 and L7×T4 stand out with high positive SCA effects, reflecting their potential to increase grain number significantly. This trait is crucial for improving yield and overall productivity in barley. Additionally, the significant SCA effects on tillers per plant observed in L7×T4 and L7×T3 indicate their potential to enhance tillering, which is beneficial for achieving higher plant density and better yield (Sallam et al., 2018; Swati et al., 2019). The SCA effects for 1000-grain weight reveal that the cross L3×T3 has a strong potential for increasing grain size, which could positively impact overall yield quality. The performance of L5×T4 and L5×T3 also highlights their ability to improve grain weight, which is crucial for achieving desirable grain quality. Finally, the positive SCA effects observed for grain yield per plant in L5×T3, L7×T4, and L7×T3 underscore their potential to significantly boost yield.

The DMR test results for the 40 barley crosses revealed significant differences in the performance of the genotypes for various yield and yield-related traits (*Table 5*). For plant height (PH), L5 × T1 (102 cm) was the tallest cross, significantly different from others, followed by L5 × T2 (100 cm), both falling into group “a”. In contrast, L7 × T3 (69.2 cm) was significantly shorter, falling into group “e”. For spike length (SL), L3 × T4 (10.3 cm) exhibited the longest spikes, significantly higher than other crosses, while L2 × T1 (7.5 cm) and L4 × T3 (7.5 cm) had the shortest spikes, belonging to group “d”. In terms of grains per spike (GPS), L5 × T3 (80.5 grains) showed the highest number, significantly outperforming other crosses, while L7 × T3 (48.5 grains) and several other crosses like L6 × T4 (49.8 grains) fell into lower groups. For tillers per plant (TPP), L5 × T4 (24.8 tillers) had the highest value, significantly differing from other crosses, while L1 × T2 and other crosses with values around 17-18 tillers fell into the lower groups. Regarding 1000-grain weight (TGW), L7 × T4 (77.9 g) had the heaviest grains, significantly outperforming others, while L6 × T2 (67 g) and other crosses in group “c” had lighter grains.

Finally, for grain yield per plant (GYP), L7 × T4 (16.9 g) exhibited the highest grain yield, significantly surpassing the other crosses, with L7 × T3 (15.6 g) also performing well. L5 × T5 (12.9 g) and L8 × T4 (12.8 g) had relatively lower yields, falling into the “cd” group. These results suggest that crosses like L7 × T4 and L5 × T3 are promising for higher yield potential, while other crosses show variability across traits with moderate performances. This improvement in yield performance is a key goal in breeding programs aimed at enhancing barley productivity (Verma et al., 2021; Bishnoi et al., 2022; Kadege et al., 2024). The SCA effects indicate that these specific crosses hold promise for enhancing various traits in barley. Selecting and utilizing these crosses in breeding programs can lead to substantial improvements in plant height, spike length, grain number, tillering, grain weight, and yield, ultimately contributing to more productive and efficient barley cultivation (Kumari et al., 2020; Saade et al., 2020).

Conclusion

This study underscores the critical role of genetic variability and heterosis in improving the yield potential of barley. The significant variation observed in both the parents and hybrids highlights the presence of diverse genetic factors that can be harnessed to enhance barley productivity. Additive genetic effects were dominant for most traits, suggesting that selective breeding based on general combining ability (GCA) can lead to substantial improvements, particularly in traits like plant height and

grain yield. However, the presence of strong specific combining ability (SCA) effects for traits such as grains per spike and tillers per plant indicates the potential of exploiting hybrid vigor to maximize yield. Hybrids like L7×T4 and L5×T3, which exhibited superior performance in key traits, demonstrate the potential for developing high-yielding barley varieties through heterosis. The study highlights the importance of incorporating both additive and non-additive genetic effects in barley breeding programs, with a focus on hybrid breeding strategies to achieve sustainable yield improvements. Ultimately, the findings provide valuable insights for enhancing barley productivity through the strategic use of genetic diversity and heterosis, offering significant potential for sustainable barley cultivation in the future.

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