

AN INTEGRATED APPROACH USING COMBINING ABILITY, HETEROSIS AND SELECTION INDICES TO IDENTIFY POTENTIAL PARENTS AND HYBRIDS IN PEARL MILLET [*Pennisetum glaucum* (L.) R. Br.]

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ABSTRACT

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is an important climate-resilient cereal crop extensively cultivated in arid and semi-arid regions. The present investigation aimed to evaluate combining ability, heterosis and selection indices for identifying potential parents and hybrid combinations for yield improvement in pearl millet. In a Line × Tester mating design, 108 F₁ hybrids were produced by crossing nine cytoplasmic male sterile (CMS) lines with twelve testers during summer of 2025, the hybrids and their parents were assessed for seven quantitative features using a Randomized Block Design with two replications. The analysis of variance indicated significant variations between genotypes for all of the variables, showing significant genetic variation. Combining ability analysis revealed that specific combining ability (SCA) variance was greater than general combining ability (GCA) variance for all traits, indicating the dominance of non-additive gene action. Among the parental lines, ICMA 1508 and ICMA 98222 were identified as superior general combiners, while GMR 250, PT 7052 and PT 7067 emerged as promising testers for yield contributing traits. Several hybrids exhibited significant positive sca effects and heterotic response for single plant yield and yield-contributing traits. The hybrids ICMA 04777 × PT 7052, ICMA 04777 × PT 7067, ICMA 02777 × PT 7065, ICMA 05888 × PT 6679 and ICMA 1508 × PT 6029 were identified as superior combinations using a novel integrated ranking approach based on per se performance, sca effects, heterosis and selection index. The predominance of non-additive gene action provides that heterosis breeding would be an effective strategy for yield improvement in pearl millet. The integrated ranking strategy developed in the present study provides a strong framework for the early identification and prioritization of superior parents and hybrids before multi-location evaluation, thereby enhancing selection efficiency in pearl millet hybrid breeding programmes.

KEYWORDS: Combining ability; Heterosis; Hybrid breeding; Line × Tester analysis; Selection index.

1. INTRODUCTION

Pearl millet (*Pennisetum glaucum* L.) is one of the most significant cereal crops, ranking after rice, wheat, maize, barley, and sorghum, and it is a staple diet for millions of people living in arid and semi-arid countries. It characterized as exceptional nutritional quality, climate resilience and dual-purpose utility as food and fodder, plays a significant role in ensuring food and nutritional security. It accounts for nearly 75% of the global millet acreage, with approximately 70% of its production concentrated in warm tropical dryland regions (Deevi et al., 2024). Its ability to withstand drought, high temperatures and low-input conditions enables successful cultivation in environments where other cereals often fail, particularly in India and Sub-Saharan Africa (Azare et al., 2020). Pearl millet contributes extensively to world food production, with an expected yearly yield of 29.16 million metric tonnes (USDA, 2025). India is the world's leading producer, cultivating the crop on 7.2 million hectares and producing 10.86 million tonnes with an average productivity of 1,507 kg ha⁻¹ in 2024-25 (UPAg, 2025).

However, the productivity of pearl millet remains constrained by several environmental stresses, coupled with the limited availability of potential parental lines possessing desirable agronomic attributes. Therefore, the production of high yielding and stable hybrids through the effective use of cytoplasmic male sterility (CMS) systems has become a prominent consideration in pearl millet breeding programs (Tasphiya et al., 2026).

The success of hybrid breeding relies on the discovery of potential parental lines and cross combinations with favourable gene effects. Combining ability study gives relevant data on the relative performance of parents and hybrids, as well as accesses into the nature of gene action influencing economically significant traits. Kempthorne (1957), line \times tester mating design is a popular method for estimating GCA and SCA, identifying superior parents and hybrids, and developing breeding strategies. General combining ability (GCA) is generally association with additive gene effects, whereas specific combining ability (SCA) reflects non-additive gene effects such as dominance and epistasis.

In addition to combining ability analysis, heterosis breeding has played a significant role in enhancing yield potential in pearl millet. The estimation of heterosis facilitates the identification of superior hybrid combinations exhibiting enhanced performance over standard checks. Likewise, selection indices provide an effective approach for simultaneous improvement of multiple traits by integrating information from several characters into a single criterion for selection. The integrated assessment of combining ability, heterosis, and selection indices provides a complete framework for identifying top parental lines and potential hybrid combinations. Recent advances in CMS-based hybrid breeding, parental diversification and hybrid seed production have considerably enhanced the efficiency of pearl millet improvement programmes. However, the identification of potential parents and hybrid combinations with high combining ability remains a key prerequisite for achieving sustained genetic gain (Yadav et al., 2024). Therefore, the present investigation was undertaken to estimate the general and specific combining ability of parental lines and hybrids, assess heterosis and selection indices for yield and its component traits, and identify superior hybrid combinations for pearl millet improvement.

2. MATERIALS AND METHODS

The present investigation was carried out at the Millet Breeding Station, CPBG, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India. The experimental material employed nine male sterile lines (lines) and twelve restorers (testers), which were crossed in a Line \times Tester mating design to produce 108 F₁ hybrids.

Crosses between the parental lines and testers were raised during Rabi 2024 in a designated crossing block, resulting in the development of 108 F₁ hybrids. During Summer 2025, the hybrids and their 21 parents were assessed in a Randomized Block Design (RBD) with two replications, maintaining a spacing of 50 \times 15 cm. Uniform agronomic and crop management practices were implemented throughout the experimental period to facilitate optimum crop growth and development.

Data on days to fifty percent flowering, plant height (cm), number of productive tillers per plant, spike length (cm), spike girth (cm), single plant yield (g) and thousand grain weight (g) were collected from five randomly tagged plants in each genotype across two replications. The resulting dataset was subjected to appropriate statistical analyses to assess the breeding potential and genetic performance of the parental lines and hybrids.

3. STATISTICAL ANALYSIS

Analysis of variance (ANOVA) was performed to assess the significant differences among genotypes for all the traits studied. Combining ability analysis was carried out following the Line \times Tester method proposed by Kempthorne (1957). General combining ability (gca) effects of parents and specific combining ability (sca) effects of hybrids were estimated for all yield and yield-contributing traits.

The variance components associated with GCA and SCA were computed to determine the relative importance of additive and non-additive gene actions governing trait inheritance.

Baker's predictability ratio was estimated using the modified equation, $2\sigma^2GCA/(2\sigma^2GCA + \sigma^2SCA)$, originally proposed by Baker (1978) and later adapted by Hung and Holland (2012).

The predictability ratio approaching unity indicates the predominance of additive gene action, whereas values approaching zero suggest the predominance of non-additive gene action. Standard heterosis was estimated as the percentage increase or decrease in hybrid performance over the standard check following the method of Fonseca and Patterson (1968). All statistical analyses were performed using R software (Version 4.6.0).]

4. RESULTS AND DISCUSSION

4.1. Analysis of Variance

The ANOVA (Table 1) indicated highly significant variation among the parental lines and hybrids for all seven quantitative traits, including days to fifty per cent flowering (DFF), plant height (PH), number of productive tillers per plant (NPTP), spike length (SL), spike girth (SG), thousand grain weight (TGW) and single plant yield (SPY). Significant variation among parents and crosses further demonstrated the diverse genetic constitution of the experimental materials and confirmed the effectiveness of the line \times tester mating design in generating variability.

The male parents also exhibited significant variation for DFF, PH and SL, while significance at the 5 per cent level was observed for SG, indicating the differential contribution of female parents towards the expression of these traits. Similarly, testers exhibited significant variation for DFF and SL, suggesting the presence of variability in male parents. The L × T interaction component was significant for all the traits studied, indicating the significance of specific parental combinations and non-additive gene effects in the inheritance of these traits. Similar findings indicating the greater influence of non-additive gene action for yield and its component traits in pearl millet were reported by Thribhuvan et al. (2023).

The significant differences observed between parents and crosses for all the characters indicated the presence of significant heterotic effects among the hybrids generated in the present study. Such heterotic expression reflects the genetic divergence between parental lines and highlights the potential of hybrid breeding for yield improvement in pearl millet. Comparable results demonstrating significant heterosis for seed yield and related traits have been reported in pearl millet by Warriar et al. (2020).

4.2. Variance Components and Nature of Gene Action

The estimates of variance components for combining ability (Table 2) revealed that the specific combining ability (SCA) variance was substantially greater than the corresponding general combining ability (GCA) variance for all the observed traits. For instance, the SCA variance for single plant yield (211.1) exceeded than GCA variance (0.611). PH, SL, SG, TWT and NPTP also exhibited a similar trend, reflecting the dominant role of non-additive gene action in governing their inheritance. Similar findings were reported by Choudhary et al. (2023), Gaoh et al. (2023) and Surendhar et al. (2023), who also observed the major contribution of SCA variance over GCA variance for yield and associated traits in pearl millet.

Baker's predictability ratio [$2\sigma^2GCA/(2\sigma^2GCA + \sigma^2SCA)$] was considerably lower than unity for all the traits, ranging from TWT (0.003) to DFF (0.064). The low Baker's predictability ratios suggest that the inheritance of these traits is primarily governed by non-additive rather than additive gene action. These results indicate that dominance and epistatic effects play a major role in the expression of yield and yield-contributing traits. Therefore, the exploitation of heterosis through hybrid breeding would be a more effective breeding strategy than direct selection for improving productivity in pearl millet. The findings of Rasitha et al. (2023) demonstrated that grain yield and related traits in pearl millet exhibited low Baker's predictability ratios and comparatively higher SCA variance than GCA variance, emphasizing the dominant contribution of non-additive gene action to trait inheritance and supporting the exploitation of heterosis for yield improvement.

4.3. Proportional Contribution of Combining Ability

The proportional contribution of lines, testers and L × T interactions towards total genetic variation also provides the influence of non-additive gene action (Table 2 and Fig. 1). The L × T interaction contributed the largest proportion of variation for all the observed traits, ranging from 43.08 per cent for days to fifty per cent flowering to 79.44 per cent for spike girth.

The highest contribution of line × tester interactions was noted for spike girth (79.44%), thousand grain weight (79.04%), number of productive tillers per plant (76.46%) and single plant yield (75.52%), indicating the greater influence of parental combinations on the expression of these traits and confirms the non-additive gene effects in the inheritance of these traits. Similar findings have been reported in pearl millet by Kumawat et al. (2019) and Warriar et al. (2020), who observed a major contribution of line × tester interactions towards the expression of yield and yield-contributing traits.

Among the parental components, lines contributed relatively higher proportions of variance than testers for plant height (39.42%), spike length (38.60%) and spike girth (16.96%), whereas testers contributed comparatively more towards days to fifty per cent flowering (30.66%) and single plant yield (12.48%). The relatively greater contribution of lines for certain traits suggests their importance in transmitting favourable alleles, while the higher contribution of testers for flowering and yield indicates their potential utility in hybrid development.

Rasitha et al. (2023) similarly reported differential contributions of lines, testers and L×T interactions towards the expression of yield and related traits in pearl millet. The proportional contribution of the parental components to trait variance is illustrated in Fig. 1. Overall, the substantial contribution of line × tester interactions towards yield component traits suggests that hybrid performance was governed largely by specific combining ability effects rather than the average performance of individual parents.

4.4. General Combining Ability Effects of Parents

The distribution of general combining ability (GCA) effects among the parental lines and testers for yield and its component traits is shown in Fig. 2. None of the parents exhibited desirable and significant gca effects for all observed traits, indicating that favourable alleles governing different traits were distributed. Similar observations were reported by Ladumor et al. (2018) and Nandaniya et al. (2016), who concluded that no single parent acts as a universal combiner for all agronomic traits. The identification of superior general combiners is important in hybrid breeding programmes because gca effects primarily reflect additive gene action and the breeding value of parental lines (Pareek et al, 2025).

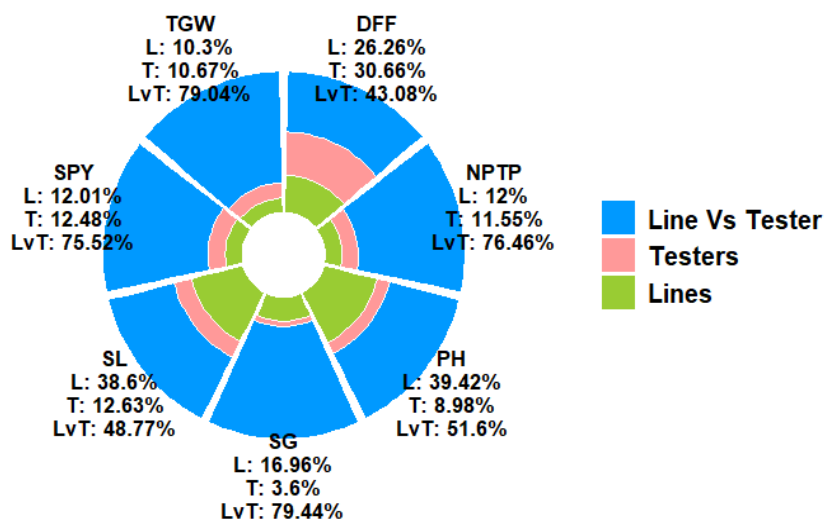


Fig.1. Relative contribution of parental components towards the total variance of quantitative traits in pearl millet

DFF – days to fifty per cent flowering, PH - plant height, NPTP - number of productive tillers per plants, SL – spike length, SG – spike girth, TGW - 1000 grain weight, SPY- Single plant yield

The GCA analysis identified considerable variation in the breeding potential of the parental genotypes (Fig. 2). Among the female parents, ICMA 1508 recorded desirable positive gca effects for single plant yield (6.58), number of productive tillers per plant (0.34), spike length (2.02), spike girth (0.25), thousand grain weight (0.62) and plant height (15.05), indicating its suitability as a parent for improving yield contributing traits. ICMA 98222 also exhibited superior gca effects for single plant yield (9.56), number of productive tillers per plant (0.25), spike girth (0.27) and thousand grain weight (0.62) and plant height (–7.20).

Among the male parents, GMR 250 expressed favourable gca effects for single plant yield (9.32) and number of productive tillers per plant (0.35). Similarly, PT 7052 showed desirable gca effects for single plant yield (9.30), number of productive tillers per plant (0.35) and thousand grain weight (0.75), whereas PT 7067 recorded positive gca effects for single plant yield (5.17), number of productive tillers per plant (0.35) and thousand grain weight (0.66). The specific combining ability exhibited by these testers demonstrates their potential to contribute favourable additive genetic effects and their suitability for developing improved pearl millet hybrids. Based on their overall gca performance for yield and associated traits, ICMA 1508 and ICMA 98222 among the lines, and GMR 250, PT 7052 and PT 7067 among the testers, were identified as promising parents for the development of high-yielding pearl millet hybrids. Likewise, Surendhar et al. (2023) reported that parents possessing high positive gca effects for grain yield component traits are valuable sources for developing superior hybrids and breeding populations

Table 1. Analysis of variance of combining ability (Line × Tester) for different quantitative characters

Source of variation	df	DFF	PH	NPTP	SL	SG	TGW	SPY
Treatments	128	27.89**	916.91**	1.12**	40.97**	0.504**	5.62**	566.11**
Parents	20	21.41**	963.44**	0.77**	66.32**	0.492**	3.24**	211.61**
Crosses	107	24.43**	545.89**	1.10**	31.61**	0.464**	5.64**	517.08**
Lines	8	85.81**	2878.11**	1.76	163.23**	1.054*	7.77	830.29
Testers	11	72.86**	476.95	1.23	38.84*	0.163	5.85	627.68
Lines x Testers	88	12.79**	342.49**	1.02**	18.74**	0.449**	5.42**	474.78**
Parents vs Crosses	1	527.99**	39685.83**	11.06**	535.60**	4.998**	51.18**	12902.68**
Error	128	2.90	24.31	0.24	6.54	0.239	1.21	44.61

*, **Significance at 5 % and 1 % Level of Probability

df - Degrees of freedom, DFF – Days to fifty per cent flowering, PH - plant height, NPTP - number of productive tillers/plants, SL – spike length, SG – spike girth, TGW - 1000 grain weight, SPY- Single plant yield

Table 2. Estimates of general and specific combining ability variance components for quantitative traits in pearl millet.

Characters	DFF	PH	NPTP	SL	SG	TGW	SPY
GCA variance	0.168	2.93	0.001	0.186	0.002	0.003	0.611
SCA variance	4.902	157.35	0.391	6.247	0.103	2.059	211.16
$2\sigma^2GCA/(2\sigma^2GCA+\sigma^2SCA)$	0.064	0.03	0.005	0.056	0.037	0.003	0.006
Proportional contribution of quantitative traits towards variance in Pearl millet							
Lines	26.26	39.42	12.00	38.60	16.96	10.30	12.01
Testers	30.66	8.98	11.55	12.63	3.60	10.67	12.48
Line Vs Tester	43.08	51.60	76.46	48.77	79.44	79.04	75.52

DFF – days to fifty per cent flowering, PH - plant height, NPTP - number of productive tillers per plants, SL – spike length, SG – spike girth, TGW - 1000 grain weight, SPY- Single plant yield

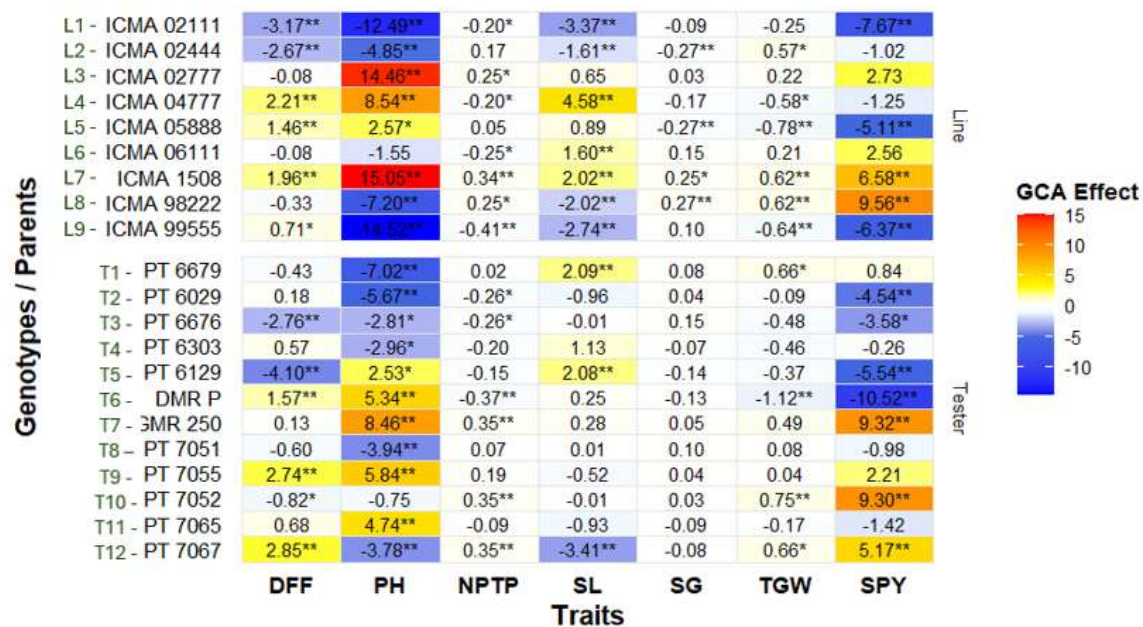


Fig.2. Heatmap representing the estimates of general combining ability (GCA) effects of parental lines and testers for quantitative traits in pearl millet.

The heatmap colour scale indicates the direction and magnitude of the GCA effects, with blue representing negative values and red representing positive values. Increasing colour intensity corresponds to greater effect magnitude. Statistical significance is denoted by * ($P \leq 0.05$) and ** ($P \leq 0.01$). The Lines and Testers indicated as L and T respectively, DFF - days to per cent flowering, PH - plant height, NPTP - number of productive tillers per plant, SL - spike length, SG - spike girth, TGW - 1000 grain weight and SPY - single plant yield.

4.5. Specific Combining Ability Effects of Hybrids

The specific combining ability (SCA) effects estimated for yield and yield-contributing traits are visualized in Fig. 3. It varied widely in both positive and negative directions for all observed traits, indicating diverse interactions among parental combinations. Significant sca effects expressed by several hybrids suggest that non-additive gene action plays a dominant role in governing yield associated traits. Similar observations were reported by Acharya et al. (2021), who highlighted the importance of specific parental combinations in enhancing hybrid performance in pearl millet.

For single plant yield, several hybrids exhibited significant positive sca effects. Among them, ICMA 02444 × DMR P recorded the highest positive sca effect, followed by ICMA 05888 × PT 7065, ICMA 05888 × PT 6679, ICMA 04777 × PT 6679, ICMA 02777 × PT 7051, ICMA 02777 × PT 6676 and ICMA 02111 × PT 7052. The superior sca effects observed in these hybrids indicate favourable parental interactions and suggest their potential for heterosis exploitation. With respect to yield-contributing traits, several crosses exhibited desirable sca effects

for multiple characters. The hybrid ICMA 02777 × PT 6676 recorded favourable sca effects for spike length, thousand grain weight and single plant yield. Another promising hybrid, ICMA 1508 × PT 6029, demonstrated favourable sca effects for plant height, number of productive tillers per plant, thousand grain weight and single plant yield. Likewise, ICMA 98222 × DMR P showed desirable combining ability for number of productive tillers per plant, thousand grain weight and single plant yield, whereas ICMA 06111 × PT 6129 exhibited positive sca effects for number of productive tillers per plant, spike length and single plant yield. The superior performance of these hybrids suggests the involvement of favourable non-additive genetic interactions in the expression of yield and related traits. Similarly, Surendhar et al. (2023) reported that hybrids with high positive sca effects for grain yield and yield-contributing traits resulted from favourable non-additive genetic interactions and represented promising candidates for heterosis exploitation in pearl millet.

The Circos plots (Fig. 3) provide a comprehensive visualization of the distribution and magnitude of sca effects among the 108 hybrid combinations across the seven quantitative traits. Among the studied traits, single plant yield (SPY) exhibited the greatest number of hybrids with significant positive sca effects, followed by plant height (PH), indicating that several line × tester combinations possessed favourable non-additive genetic interactions for these yield contributing traits. The Circos analysis further revealed that female lines ICMA 04777 (L4), ICMA 05888 (L5), ICMA 02777 (L3) and ICMA 1508 (L7) formed several superior hybrid combinations with testers DMR P (T6), PT 6679 (T1), PT 7051 (T8), PT 7052 (T10) and PT 7065 (T11), exhibiting desirable positive sca effects for single plant yield along with other important yield-contributing traits. Conversely, only a limited number of hybrid combinations recorded favourable sca effects for number of productive tillers per plant (NPTP), spike girth (SG) and thousand grain weight (TGW), suggesting that the expression of these traits depends on specific parental interactions. The wide variation in both positive and negative sca effects observed across the studied traits reflects the diverse genetic interactions among the parental combinations and supports the greater contribution of non-additive gene action.

The overall distribution of specific combining ability (sca) effects across the seven quantitative traits is presented in Fig. 4. The boxplots summarize the distribution of sca effects among the 108 hybrid combinations evaluated for each trait and revealed the variability in both the magnitude and direction of specific combining ability. Among the studied traits, single plant yield (SPY) exhibited the widest distribution of sca effects with a relatively higher median value, indicating the presence of several hybrid combinations possessing favourable non-additive genetic interactions for yield improvement. Plant height (PH), spike length (SL) and spike girth (SG) also displayed considerable variability, reflecting differential line × tester interactions governing the expression of these traits. In contrast, number of productive tillers per plant (NPTP) and thousand grain weight (TGW) exhibited relatively narrower distributions, suggesting comparatively fewer hybrid combinations with extreme sca effects. The presence of several extreme observations beyond the whiskers, particularly for SPY and PH, indicates the presence of hybrid combinations with exceptionally high or low sca effects, reflecting strong non-additive interactions between specific parental combinations. The variability observed in sca effects among the hybrid combinations reflects differences in the genetic interactions between parental genotypes. These observations are consistent with the combining ability variance analysis, which demonstrated the greater importance of non-additive genetic effects in controlling the studied traits. Hence, evaluation of the overall sca distribution provides an effective approach for recognizing promising hybrids with superior combining ability for yield and its associated traits.

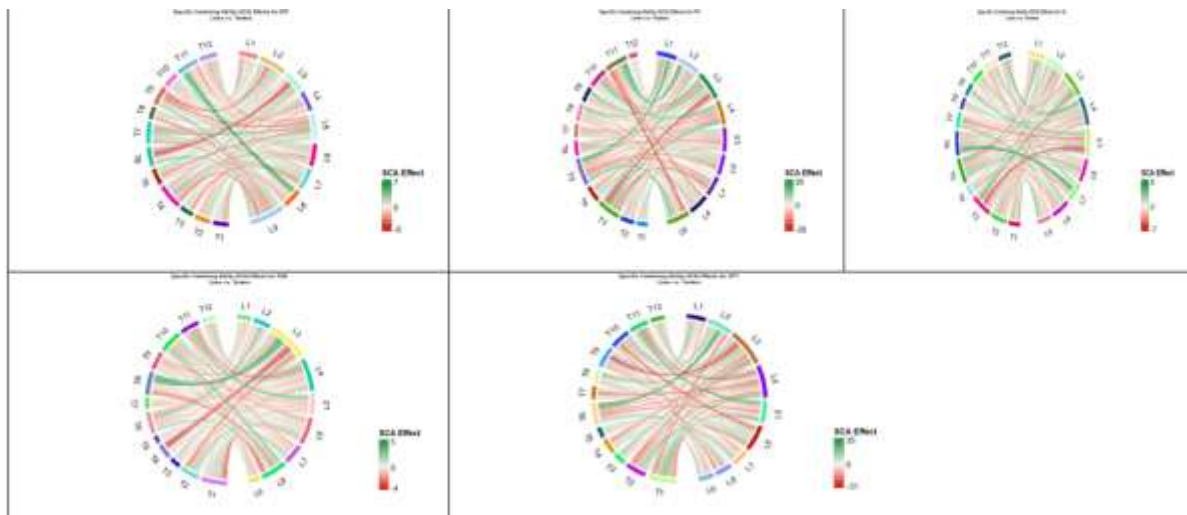


Fig 3. Estimates of specific combining ability (sca) effects of crosses for yield and its attributing characters Circos plots displaying the sca effects of 108 hybrids for seven traits. The outer arcs represent the parental lines (L1–L9) and testers (T1–T12), while the ribbons indicate individual cross combinations. Green ribbons denote positive sca effects and red ribbons denote negative sca effects, with colour intensity corresponding to the magnitude of the sca effect as shown in the colour scale. For DFF, negative sca effects are considered desirable, whereas for PH, NPTP, SL, SG, TGW and SPY, positive sca effects are considered desirable. DFF - days to 50 per cent flowering, PH - plant height, NPTP - number of productive tillers per plant, SL - spike length, SG - spike girth, TGW - 1000 grain weight and SPY - single plant yield.

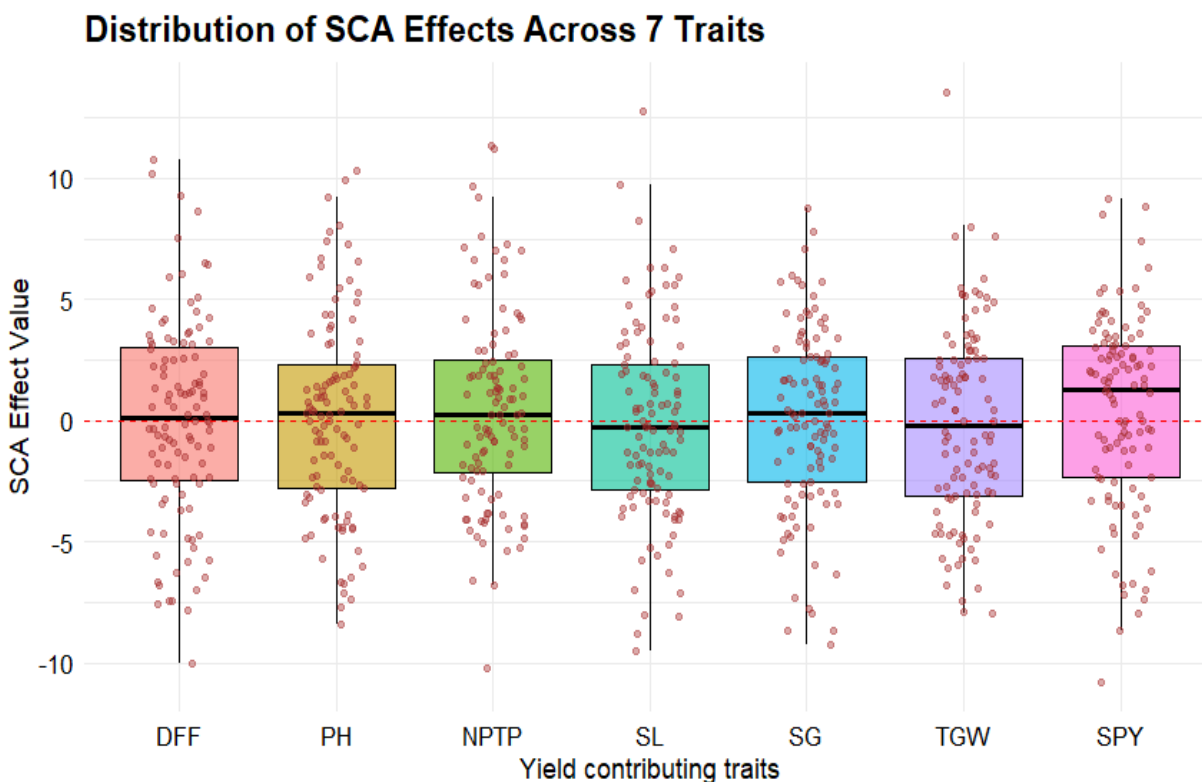


Fig. 4. Overall distribution of specific combining ability (sca) effects for yield and its attributing characters in pearl millet.

Distribution of specific combining ability (SCA) effects for 108 hybrids across seven quantitative traits illustrated using boxplots. The boxes indicate the interquartile range (IQR), the median is represented by the horizontal line within each box, and the whiskers extend to 1.5 times the IQR. Individual points represent sca effects of individual hybrid combinations. The red dashed line denotes the zero-effect reference. DFF - days to 50 per cent flowering, PH - plant height, NPTP - number of productive tillers per plant, SL - spike length, SG - spike girth, TGW - 1000 grain weight and SPY - single plant yield.

4.6. Relationship between per se, gca effects and selection index among parents.

The evaluation of parental breeding value was based on the integration of three complementary parameters: per se performance, general combining ability (gca) effects, and the selection index. Per se performance, popularized by Allard (1960), represents the phenotypic performance of a parent and serves as a preliminary criterion for selecting superior genotypes. However, superior per se performance alone may not reliably predict hybrid performance because of the influence of non-additive gene action. To estimate the additive genetic contribution of parents, Sprague and Tatum (1942) introduced the concept of general combining ability (GCA), which reflects the average performance of a parent across multiple hybrid combinations. To facilitate simultaneous improvement of several economically important traits, the selection index approach (Smith, 1936; Hazel, 1943) combines information from multiple characters into a single weighted value, thereby enhancing selection efficiency.

A multi-parameter integrated ranking approach was employed to prioritize parental lines and hybrids based on five important quantitative traits: days to 50% flowering (DFF), plant height (PH), spike length (SL), thousand-grain weight (TGW) and single-plant yield (SPY). Parents were ranked independently based on per se performance, gca effects and selection index values. The relationships among these parameters were examined through correlation analysis to assess the agreement between phenotypic performance and additive genetic merit. The individual ranks were subsequently summed to obtain the Parental Cumulative Rank (PCR), which enabled the comprehensive assessment and prioritization of parental lines. Parents with the lowest PCR values were considered superior owing to their consistent phenotypic performance, favourable combining ability and overall breeding potential. The top ten parents identified through cumulative ranking are presented in Tables 3a and 3b. This integrated approach provides a robust framework for selecting elite parental lines for hybrid development and population improvement programmes in pearl millet, consistent with similar multi-criteria selection strategies reported in crop breeding studies (Liu et al., 2021).

Among the selected parents, ICMA 1508 emerged as the most promising parent, securing the first overall rank with the highest selection index and lowest cumulative rank score. Its superiority was attributed to favourable per se performance for spike length, thousand grain weight and single plant yield, together with desirable gca effects for plant height, spike length, thousand grain weight and single plant yield. ICMA 04777 and ICMA 05888 ranked second and third, respectively, due to their favourable performance across multiple yield-related traits and superior overall ranking parameters. GMR 250 and ICMA 98222 were also identified as valuable parental lines. GMR 250 recorded the highest per se performance for plant height and single plant yield, whereas ICMA 98222 exhibited the highest positive gca effect for single plant yield and favourable gca effects for thousand grain weight and other yield-associated traits. Likewise, PT 6679 and PT 7067 displayed desirable GCA effects for yield and associated traits, highlighting their potential utility in breeding programmes.

Overall, the integrated evaluation of per se performance, gca effects and selection index identified ICMA 1508, ICMA 04777, ICMA 05888, GMR 250 and ICMA 98222 as the most promising parental lines for pearl millet improvement. The integration of favourable phenotypic performance with desirable additive genetic effects provided the breeding value of these parents for generating superior hybrids and broadening the genetic base of future breeding populations.

4.7. Relationship between per se, sca effects, heterosis and selection index among hybrids.

An integrated evaluation of hybrid performance utilizes a multi-dimensional matrix incorporating per se performance, Specific Combining Ability (sca) effects, standard heterosis, and selection indices to identify superior germplasm. While per se performance (Allard, 1960) provides the base phenotypic value, SCA effects (Sprague and Tatum, 1942) identify high-value parental combinations driven by non-additive gene action, with standard heterosis (Shull, 1914) providing a metric for commercial superiority. The selection index (Smith, 1936) acts as a balancing tool for multiple traits, allowing for the calculation of a Hybrid Cumulative Rank (HCR) that filters for stable, elite pearl millet hybrids among the 108 hybrids with both high yield and desirable secondary traits. This approach systematically isolates high-performing crosses for commercial release. The top twenty hybrids selected based on cumulative ranking are presented in Tables 4a and 4b. Among the selected hybrids, ICMA 04777 × PT 7052 emerged as the most promising combination, securing the first overall rank with the lowest cumulative rank score. Its superiority was attributed to favourable per se performance for thousand grain weight and single plant yield, coupled with desirable sca effects and high heterotic response for these traits. The consistent performance of this hybrid across multiple evaluation criteria highlights its potential for exploitation in pearl millet improvement programmes.

Among the selected hybrids, ICMA 04777 × PT 7052 emerged as the most promising hybrid combination, securing the first overall rank with the lowest cumulative ranking score. Its superiority was attributed to favourable per se performance for thousand grain weight and single plant yield, coupled with desirable sca effects, high heterotic response and a superior selection index. The hybrids ICMA 04777 × PT 7067 and ICMA 02777 × PT 7065 ranked second and third, respectively, due to their superior performance in per se performance, sca effects, The superior performance of these hybrids indicates the involvement of favourable non-additive genetic interactions in the expression of yield and related traits. Comparable observations were reported by Siddique et al. (2022), who found that hybrids exhibiting high SCA effects also expressed superior heterotic performance for grain yield, indicating the contribution of favourable parental combinations to hybrid vigour. ICMA 04777 × PT

7067 exhibited desirable sca effects and high heterotic response for spike length, thousand grain weight and yield-related traits, whereas ICMA 02777 × PT 7065 demonstrated favourable overall performance with desirable combining ability and substantial heterotic response across multiple characters. Similarly, ICMA 05888 × PT 6679, ICMA 1508 × PT 6029, ICMA 02777 × GMR 250 and ICMA 05888 × PT 7065 consistently performed well across several breeding parameters, resulting in their placement among the top-ranked hybrid combinations. Several hybrids also exhibited superiority for specific traits. ICMA 02777 × PT 7051 recorded the highest thousand grain weight among the selected hybrids, while ICMA 98222 × PT 7052 expressed superior per se performance for thousand grain weight and single plant yield. Likewise, ICMA 1508 × DMR P and ICMA 04777 × PT 7055 exhibited high heterotic responses for yield-contributing traits, indicating their potential utility in future hybrid breeding programmes.

Overall, the integrated evaluation of per se performance, specific combining ability (sca) effects, heterosis and selection index identified ICMA 04777 × PT 7052, ICMA 04777 × PT 7067, ICMA 02777 × PT 7065, ICMA 05888 × PT 6679 and ICMA 1508 × PT 6029 as the most promising hybrid combinations among the 108 hybrids evaluated. The superiority of these hybrids across multiple breeding parameters demonstrates the effectiveness of an integrated ranking approach in identifying elite hybrid combinations with superior genetic potential for yield improvement. Rather than relying on a single selection criterion, the integration of per se performance, sca effects, heterosis and selection index enables the simultaneous evaluation of phenotypic performance, non-additive genetic effects and overall breeding value, thereby facilitating the identification of stable and high-performing hybrids. A comparable integrated selection strategy was recently proposed by Pareek et al. (2025), who developed a Product Rating Index (PRI) for rapid hybrid advancement. However, the present study further strengthens hybrid selection by integrating multiple genetic and breeding parameters, thereby enhancing selection efficiency before multi-location evaluation.

Table 3a. Integrated evaluation of parental lines based on per se performance for yield and its associated traits in pearl millet

S.No.	Parents	Per se performance (Rank)										Avg of Rank	
		DFF		PH		SL		TGW		SPY			
		Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank		
1	ICMA 1508	47.5	1	19	131.57	15	28.85	3	10.24	6	77.52	10	11
2	ICMA 04777	48.5	1	20	124.93	18	39.00	1	9.20	14	78.40	9	12
3	ICMA 05888	44.5	5	15	127.96	17	27.86	6	10.19	7	72.00	13	12
4	GMR 250	44.3	2	14	188.12	1	25.19	9	11.29	2	97.45	1	5
5	ICMA 98222	44.0	1	12	123.08	19	17.29	20	12.31	1	83.38	4	11
6	PT 6679	43.5	9	11	155.63	11	27.57	7	9.95	8	82.24	5	8
7	PT 6029	37.8	0	1	159.48	9	27.88	5	8.61	17	71.65	14	9
8	ICMA 99555	43.0	7	10	150.07	13	22.57	14	10.44	4	74.53	12	11
9	PT 7067	38.2	5	2	164.14	6	20.41	17	9.07	15	80.69	7	9
10	ICMA 06111	44.1	4	13	102.42	21	24.61	11	9.34	10	70.06	15	14

Table 3b. Integrated evaluation of parental lines based on gca effects, selection index and cumulative ranking in pearl millet

S.No	Parents	gca effects (Rank)						Avg. of rank	Selection index	Parental Cumulative Rank
		Dff	PH	SL	TGW	SPY				

		Val ue	Ra nk	Val ue	Ra nk	Val ue	Ra nk	Val ue	Ra nk	Val ue	Ra nk		Value	Ra nk	
1	ICMA 1508	1.96	4	15.0 5	1	2.02	4	0.62	4	6.58	4	3	349.2 26	1	1
2	ICMA 04777	2.21	3	8.54	3	4.58	1	- 0.58	18	- 1.25	13	8	302.7 02	5	2
3	ICMA 05888	1.46	6	2.57	8	0.89	7	- 0.78	20	- 5.11	17	12	321.3 29	2	3
4	GMR 250	0.13	11	8.46	4	0.28	9	0.49	7	9.32	2	7	282.5 01	14	4
5	ICMA 98222	- 0.33	14	- 7.20	19	- 2.02	18	0.62	4	9.56	1	11	307.7 56	4	5
6	PT 6679	- 0.43	15	- 7.02	18	2.09	2	0.66	2	0.84	9	9	297.9 54	9	6
7	PT 6029	0.18	10	- 5.67	17	- 0.96	16	- 0.09	12	- 4.54	16	14	299.9 69	7	7
8	ICMA 99555	0.71	7	- 14.5 2	21	- 2.74	19	- 0.64	19	- 6.37	19	17	310.7 33	3	8
9	PT7067	2.85	1	- 3.78	14	- 3.41	21	0.66	2	5.17	5	9	283.4 59	13	9
10	ICMA 06111	- 0.08	12	- 1.55	11	1.60	5	0.21	9	2.56	7	9	293.0 85	10	10

Table 4a. Integrated evaluation of hybrid combinations based on per se performance for yield and its component traits in pearl millet

S.N o.	Hybrids	Per se performance (Rank)											
		DFP		PH		SL		TGW		SPY		Avg of Rank	
		Val ue	Ra nk	Val ue	Ra nk	Val ue	Ra nk	Val ue	Ra nk	Val ue	Ra nk		
1	ICMA 04777 × PT 7052	50.9 6	87	211. 48	4	32.0 4	17	13.1 7	5	116. 10	11	21	
2	ICMA 04777 × PT 7067	54.0 5	107	193. 18	28	35.0 3	8	13.1 4	7	117. 37	9	27	
3	ICMA 02777 × PT 7065	47.9 0	59	222. 92	2	30.1 1	35	12.5 9	12	112. 79	22	22	
4	ICMA 05888 × PT 6679	50.8 8	85	192. 85	30	30.8 3	23	12.3 7	18	116. 13	10	28	
5	ICMA 1508 × PT 6029	50.2 3	77	205. 29	11	28.2 5	51	12.9 4	9	116. 04	12	27	
6	ICMA 02777 × GMR 250	46.3 3	47	210. 40	7	30.0 2	37	12.4 4	16	117. 46	7	19	
7	ICMA 05888 × PT 7065	48.4 5	62	203. 04	16	28.1 0	53	12.8 4	11	117. 70	6	25	
8	ICMA 1508 × PT 7067	50.2 0	76	204. 03	13	30.6 1	28	13.0 7	8	112. 53	24	25	
9	ICMA 1508 × PT 6679	47.0 2	53	196. 50	24	31.7 7	19	14.0 0	3	115. 59	15	19	
10	ICMA 02777 × PT 7051	48.2 8	61	182. 86	48	30.5 6	29	15.8 4	1	119. 68	2	24	
11	ICMA 04777 × PT 6679	49.7 6	75	178. 97	61	35.4 0	6	12.5 1	14	117. 99	4	27	
12	ICMA 1508 × GMR 250	52.5 0	98	204. 99	12	30.0 7	36	12.5 4	13	106. 33	36	33	
13	ICMA 1508 × PT 6303	53.5 2	104	203. 69	14	28.6 0	49	10.8 5	43	113. 05	20	38	
14	ICMA 04777 × PT 7051	52.1 8	96	187. 30	41	36.3 6	4	11.1 0	37	103. 09	40	36	

15	ICMA 98222 × GMR 250	49.60	72	191.40	33	30.69	26	11.29	36	113.85	19	31
16	ICMA 98222 × PT 7052	44.62	30	182.69	50	28.80	48	15.03	2	120.82	1	22
17	ICMA 1508 × DMR P	52.01	95	210.43	6	37.63	1	10.29	63	88.28	64	38
18	ICMA 04777 × PT 7055	52.00	94	209.08	9	32.81	12	9.67	80	105.29	38	39
19	ICMA 02777 × PT 6679	47.48	56	188.10	40	28.94	43	12.90	10	115.68	14	27
20	ICMA 04777 × PT 6676	48.67	64	210.76	5	30.50	31	10.30	62	98.99	46	35

Table 4b. Integrated evaluation of hybrid combinations based on specific combining ability (sca) effects for yield and its contributing traits in pearl millet

S.No.	Hybrids	sca effects (Rank)										Avg. of Rank
		DFP		PH		SL		TGW		SPY		
		Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	
1	ICMA 04777 × PT 7052	2.07	24	20.92	5	-0.65	55	2.36	7	13.24	22	19
2	ICMA 04777 × PT 7067	1.40	35	5.65	36	5.74	3	2.42	5	18.64	11	15
3	ICMA 02777 × PT 7065	-0.14	59	20.96	4	2.28	27	1.9	10	16.67	14	19
4	ICMA 05888 × PT 6679	1.93	27	14.53	12	-0.27	51	1.85	11	25.59	3	17
5	ICMA 1508 × PT 6029	0.32	49	13.14	14	-0.93	59	1.77	14	19.18	10	24
6	ICMA 02777 × GMR 250	-1.58	78	4.71	40	0.98	35	1.09	22	10.59	28	34
7	ICMA 05888 × PT 7065	-1.18	71	12.97	15	0.03	46	3.15	3	29.42	2	23
8	ICMA 1508 × PT 7067	-2.35	93	9.99	24	3.89	12	1.16	20	5.97	39	31
9	ICMA 1508 × PT 6679	-2.07	89	5.71	35	-0.45	54	2.08	9	13.35	20	35
10	ICMA 02777 × PT 7051	1.64	31	-10.42	87	1.79	31	4.9	1	23.12	5	26
11	ICMA 04777 × PT 6679	0.68	42	-5.32	74	0.61	39	1.79	13	23.58	4	29
12	ICMA 1508 × GMR 250	2.88	9	-1.28	56	-0.34	52	0.79	31	-4.39	64	35
13	ICMA 1508 × PT 6303	3.43	6	8.83	27	-2.66	91	0.06	53	11.91	24	34
14	ICMA 04777 × PT 7051	2.85	11	-0.07	52	3.66	14	0.97	27	10.51	29	22
15	ICMA 98222 × GMR 250	2.17	22	7.38	32	4.33	8	-0.45	70	0.16	53	31
16	ICMA 98222 × PT 7052	-1.89	84	7.87	31	2.72	24	3.02	4	7.16	35	30
17	ICMA 1508 × DMR P	0.93	41	7.27	33	7.25	1	0.16	48	-2.6	58	30
18	ICMA 04777 × PT 7055	-0.49	64	11.94	18	0.64	38	0.42	67	9.52	33	37
19	ICMA 02777 × PT 6679	0.47	47	-2.10	57	-1.92	78	1.38	16	17.3	13	35

20	ICMA 04777× PT 6676	2.01	26	22.2	7	3	-	2.18	81	0.72	32	9.01	34	29
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Table 4c. Integrated evaluation of hybrid combinations based on heterosis, selection index and cumulative ranking in pearl millet

S. No	Hybrids	Heterosis											SI		Hybrid Cumulative Rank
		DFE		PH		SL		TGW		SPY		Av g. of Rank	Val ue	Ra nk	
		Val ue	Ra nk	Val ue	Ra nk	Val ue	Ra nk	Val ue	Ra nk	Val ue	Ra nk				
1	ICMA 04777 × PT 7052	22.81	22	45.85	4	31.25	17	49.41	5	65.37	11	10	387.04	2	1
2	ICMA 04777 × PT 7067	30.24	2	33.22	28	43.51	8	48.97	7	67.17	9	9	377.52	4	2
3	ICMA 02777 × PT 7065	15.43	50	53.74	2	23.37	35	42.75	12	60.65	22	20	389.20	1	3
4	ICMA 05888 × PT 6679	22.60	24	33.00	30	26.28	23	40.31	18	65.40	10	18	367.63	12	4
5	ICMA 1508 × PT 6029	21.05	32	41.58	11	15.71	51	46.74	9	65.27	12	19	376.22	5	5
6	ICMA 02777 × GMR 250	11.65	63	45.10	7	22.99	37	41.11	16	67.30	7	22	379.33	3	6
7	ICMA 05888 × PT 7065	16.76	47	40.03	16	15.13	53	45.63	11	67.64	6	22	373.76	9	7
8	ICMA 1508 × PT 7067	20.96	33	40.71	13	25.41	28	48.27	8	60.28	24	18	374.65	8	8
9	ICMA 1508 × PT 6679	13.31	57	35.52	24	30.14	19	58.82	3	64.63	15	20	369.04	11	9
10	ICMA 02777 × PT 7051	16.35	48	26.11	48	25.20	29	79.64	1	70.46	2	21	361.68	17	10
11	ICMA 04777 × PT 6679	19.92	34	23.42	61	45.00	6	41.84	14	68.05	4	20	360.72	18	11
12	ICMA 1508 × GMR 250	26.51	11	41.37	12	23.18	36	42.22	13	51.45	36	18	372.01	10	12
13	ICMA 1508 × PT 6303	28.97	5	40.47	14	17.17	49	23.07	43	61.01	20	22	374.73	7	13
14	ICMA 04777 × PT 7051	25.74	13	29.17	41	48.97	4	25.95	37	46.84	40	23	357.92	20	14
15	ICMA 98222 × GMR 250	19.53	37	32.00	33	25.73	26	28.09	36	62.16	19	25	362.41	16	15
16	ICMA 98222 × PT 7052	7.52	79	25.99	50	17.96	48	70.47	2	72.09	1	30	355.87	23	16
17	ICMA 1508 × DMR P	25.32	14	45.12	6	54.16	1	16.75	63	25.73	64	25	367.40	13	17
18	ICMA 04777 × PT 7055	25.31	15	44.19	9	34.41	12	9.72	80	49.97	38	26	375.02	6	18
19	ICMA 02777 × PT 6679	14.42	53	29.72	40	18.54	43	46.31	10	64.76	14	27	358.23	19	19
20	ICMA 04777× PT 6676	17.29	45	45.35	5	24.96	31	16.79	62	41.00	46	32	366.25	14	20

4.8. Inter-relationship among Combining Ability Effects, Heterosis and Selection Index

Association among specific combining ability (*sca*) effects, heterosis and selection index revealed several significant positive associations among the studied parameters, highlighting the close relationships between non-additive gene action, heterotic response and hybrid performance in pearl millet (Fig. 5). Correlogram provides a comprehensive analysis of the strength and direction of these associations, where larger blue circles indicate stronger positive correlations and smaller circles represent comparatively weaker relationships. A distinct clustering of *sca* effects, heterosis and selection index was observed for major yield-contributing traits, indicating their coordinated influence on hybrid performance.

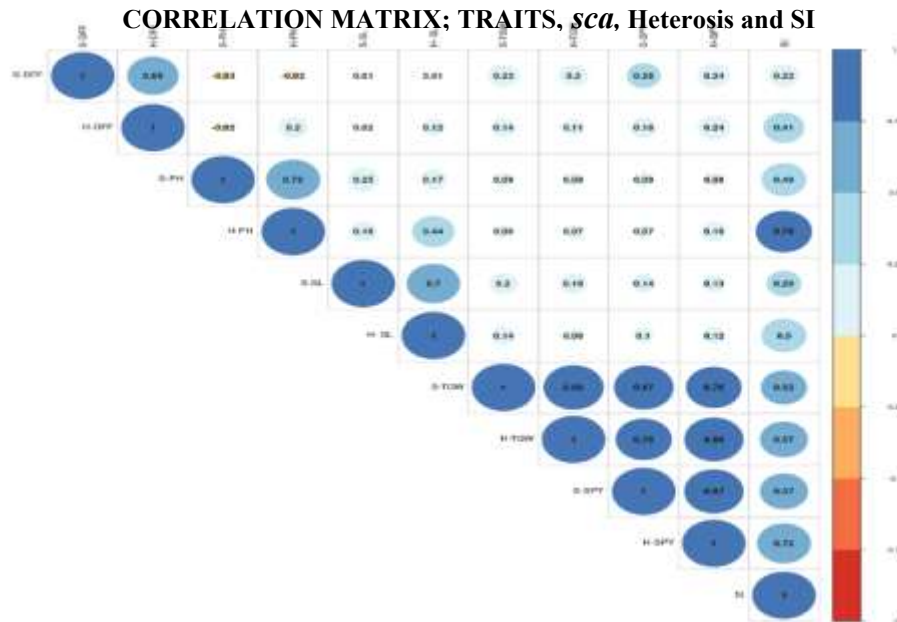


Fig. 5. Correlation matrix among combining ability effects, heterosis and selection index for yield contributing traits in pearl millet.

Correlation coefficients are visualized using circles whose diameter corresponds to the strength of the relationship, while colour denotes its direction. Blue represents positive correlations and red represents negative correlations, with the colour intensity varying according to the scale shown alongside the figure. S and H represent specific combining ability (*sca*) and heterosis effects, respectively, while SI denotes the selection index. DFF - days to fifty per cent flowering, PH - plant height, NPTP - number of productive tillers per plant, SL - spike length, SG - spike girth, TGW - 1000 grain weight and SPY - single plant yield.

A highly significant positive correlation was observed between *sca* effects and heterosis for days to fifty per cent flowering ($r = 0.65^{***}$), plant height ($r = 0.72^{***}$), spike length ($r = 0.70^{***}$) and thousand grain weight ($r = 0.89^{***}$), indicating that hybrids possessing higher *sca* effects generally exhibited greater heterotic responses for these traits. Similarly, *sca* effects for single plant yield showed a strong positive association with heterosis for single plant yield ($r = 0.87^{***}$). These relationships showed that superior hybrid performance is closely associated with favourable specific parental interactions and further confirm the predominance of non-additive gene action governing yield and its component traits. Acharya et al. (2021) similarly reported that hybrids possessing significant positive *sca* effects for grain yield and associated traits exhibited higher heterotic responses, demonstrating the close relationship between non-additive gene action and heterosis in pearl millet. Likewise, *sca* effects for thousand grain weight were strongly associated with *sca* effects for single plant yield ($r = 0.87^{***}$), while heterosis for thousand grain weight exhibited a highly significant positive correlation with heterosis for single plant yield ($r = 0.86^{***}$).

The selection index exhibited significant positive correlations with heterosis for plant height ($r = 0.78^{***}$), heterosis for single plant yield ($r = 0.72^{***}$), *sca* effects for single plant yield ($r = 0.57^{***}$), heterosis for thousand grain weight ($r = 0.57^{***}$) and *sca* effects for thousand grain weight ($r = 0.52^{***}$). The close association of the selection index with *sca* effects and heterotic responses, as evident from the correlogram, demonstrates that the selection index effectively integrates information from combining ability, heterosis and yield-contributing traits into a single selection criterion. Therefore, it provides a reliable and objective approach for identifying superior hybrid combinations with high breeding potential. Similar multi-trait selection approaches were reported by Liu et al. (2021), who demonstrated that integrating multiple breeding parameters into a comprehensive selection index improves the efficiency and accuracy of identifying superior genotypes for crop improvement. The correlogram further revealed a significant clustering among thousand grain weight and single plant yield across *sca* effects, heterosis and selection index, indicating that these parameters are closely interrelated in determining

hybrid performance. The consistently strong positive associations involving thousand grain weight suggest that this trait plays a important role in yield determination and can serve as an effective indirect selection. Overall, the strong positive associations among sca effects, heterosis and selection index demonstrate the effectiveness of integrating these breeding parameters for the identification of elite hybrid combinations in pearl millet. These findings are consistent with those of Punia et al. (2026), who demonstrated that integrating combining ability, heterosis and multi-trait selection indices provides a robust framework for ranking pearl millet hybrids and identifying superior hybrid combinations with high breeding value for crop improvement.

5. CONCLUSION

The present investigation revealed substantial genetic variability among the parental lines and hybrids for all the quantitative traits studied, indicating considerable scope for genetic improvement in pearl millet. The combining ability analysis indicated that non-additive gene action played a major role in the inheritance of yield and yield-contributing traits, as reflected by higher SCA variance than GCA variance, lower Baker's predictability ratios and the substantial contribution of $L \times T$ interactions. These findings showed that dominance and epistatic gene effects predominantly govern the inheritance of yield and its associated traits, suggesting that heterosis breeding should be the primary strategy for enhancing grain yield in pearl millet. Nevertheless, the identification of superior general combiners also indicates the potential of recurrent selection and recombination breeding for accumulating favourable additive alleles in future breeding populations.

A major outcome of the present study is the development of an integrated ranking framework that combines per se performance, combining ability effects (gca and sca), heterosis and selection index to comprehensively evaluate both parental lines and hybrid combinations. Using this multi-parameter approach, ICMA 1508, ICMA 04777, ICMA 05888, GMR 250 and ICMA 98222 were identified as superior parents, while ICMA 04777 \times PT 7052, ICMA 04777 \times PT 7067, ICMA 02777 \times PT 7065, ICMA 05888 \times PT 6679 and ICMA 1508 \times PT 6029 emerged as elite hybrid combinations with consistently superior performance across multiple breeding criteria.

Correlogram analysis further demonstrated strong positive associations among sca effects, heterosis and selection index, confirming that integrating these parameters provides a reliable basis for identifying superior hybrids. The inclusion of advanced visualization approaches, including GCA heatmaps, circos plots, SCA distribution boxplots and correlation matrices, further strengthened the interpretation of combining ability and hybrid performance by enabling rapid identification of promising parental combinations and trait relationships.

The integrated ranking strategy proposed in this study provides a practical and robust decision-support tool for pearl millet breeding. By simultaneously considering phenotypic performance and genetic potential, this approach enables more effective prioritization of superior parents and hybrids than reliance on any single selection criterion alone. Although multi-location stability evaluation remains essential before commercial release, the proposed ranking methodology can substantially improve the efficiency of early-generation selection by identifying the most promising breeding materials for further evaluation. This integrated methodology may therefore serve as a valuable breeding pipeline for accelerating hybrid development and genetic improvement in pearl millet.

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