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ASSESSMENT OF HETEROSIS AND COMBINING ABILITY FOR KERNEL YIELD AND YIELD RELATED TRAITS IN MAIZE (*Zea mays* L.)

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ABSTRACT

Identification of superior parental lines and hybrid combinations is a prerequisite for the development of high yielding maize hybrids. The present investigation was undertaken to estimate combining ability and heterosis for yield and its associated traits in maize (*Zea mays* L.) using a line × tester mating design. Seven inbred lines were crossed with seven testers to generate 49 F_1 hybrids, which along with their parents and a commercial check (GAYMH-1), were evaluated during *rabi* 2024–25 at the Main Maize Research Station, Anand Agricultural University, Godhra, India, in a randomized block design with three replications. Observations were recorded on six quantitative traits, namely days to 50% tasselling, plant height, ear height, number of kernel row per cob, 100 kernel weight and kernel yield per plant. Analysis of variance revealed highly significant differences among genotypes for all the traits indicating substantial genetic variability. Combining ability analysis showed the involvement of both additive and non-additive gene actions in the inheritance of the studied characters. Among the parents, IL-17-76, IL-15-19 and IGI-19-09 were identified as superior general combiners for kernel yield per plant while IL-14-39 was the best tester. The hybrid IL-15-19 × IL-14-39 exhibited the highest positive specific combining ability effect and the highest standard heterosis for kernel yield per plant whereas GYL-10 × IL-12-17 recorded the highest heterobeltiosis. Other promising hybrids included IL-17-76 × IGI-19-29, IL-15-19 × IGI-19-53 and IL-17-01 × IL-12-17, which expressed superior SCA effects and heterotic performance. The predominance of non-additive gene action for kernel yield suggests considerable scope for exploiting heterosis in maize improvement. The identified superior parental lines may be utilized as donor parents in breeding programmes, while the promising hybrids warrant further multi location evaluation to confirm their yield stability and suitability for commercial hybrid development.

Key words : Maize, Combining ability, Heterosis, Line × Tester, Kernel yield.

Introduction

Maize (*Zea mays* L.) is one of the world's most important cereal crops, serving as a staple food, livestock feed, and industrial raw material. Owing to its wide adaptability, high productivity and diverse end uses, maize contributes significantly to global food and nutritional security as well as the bio-based economy (FAO, 2024). It ranks third among cereal crops after wheat and rice in terms of global production and plays a vital role in the agricultural economies of both developed and developing countries. In India, despite a steady increase in maize cultivation, productivity remains lower than that of many leading maize producing countries. Therefore, continuous genetic improvement through efficient breeding strategies is essential to meet the increasing demand for grain and industrial utilization (Hasanain *et al.*, 2024).

The remarkable success of maize breeding has largely been attributed to the exploitation of heterosis, which has substantially enhanced grain yield and overall productivity since the commercial introduction of hybrid maize (He *et al.*, 2024). Heterosis refers to the superior performance of F_1 hybrids over their parents and is

commonly measured as heterobeltiosis (superiority over the better parent) and standard heterosis (superiority over a commercial check) (Paril *et al.*, 2024). The effective exploitation of heterosis depends on the identification of genetically diverse parents possessing superior combining ability. Combining ability analysis partitions genetic variation into general combining ability (GCA), which reflects additive gene effects and specific combining ability (SCA), which represents non-additive gene effects such as dominance and epistasis. Estimation of these genetic components provides valuable information for selecting suitable parents and designing efficient breeding programmes (Oladiran *et al.*, 2026).

Among the various mating designs available, the line × tester method proposed by Kempthorne (1957) is one of the most reliable and widely used approaches for evaluating combining ability and identifying superior hybrid combinations. This method is particularly useful for assessing the breeding potential of inbred lines and determining the relative contribution of additive and non-additive gene action governing economically important traits. Grain yield in maize is a complex quantitative trait controlled by numerous genes and is highly influenced by environmental factors. Consequently, selection based solely on the *per se* performance of parental lines is often inadequate for predicting hybrid performance. Therefore, simultaneous evaluation of yield and its component traits, together with combining ability and heterosis analysis, provides a more reliable basis for identifying superior parental combinations (Goud *et al.*, 2025 and Reddy *et al.*, 2026).

Several studies have demonstrated the importance of combining ability analysis in maize improvement. However, the combining ability and hybrid performance of parental lines vary considerably across different genetic backgrounds, heterotic groups, environments and breeding materials. Therefore, parental lines should be evaluated within the target breeding population to identify superior combiners and stable hybrid combinations (Engida *et al.*, 2024 and Oladiran *et al.*, 2026).

Most previous studies have focused on specific sets of germplasm whereas information regarding the combining ability and heterotic potential of newly developed inbred lines under the agro-climatic conditions of Gujarat remains limited. Therefore, evaluating locally developed breeding materials is essential for identifying superior parents and hybrids suitable for future hybrid development programmes.

In view of this research gap, the present investigation was undertaken to evaluate the combining ability and heterotic performance of selected maize inbred lines using a line × tester mating design. The specific objectives were: (i) to estimate heterosis for kernel yield and its associated traits; (ii) to assess the general and specific combining ability effects of parental lines and their hybrids; (iii) to identify superior general combiners and promising hybrid combinations and (iv) to select elite crosses with high yield potential for further multi-location evaluation and utilization in maize hybrid breeding programmes.

Materials and Methods

Plant materials

The experimental material comprised fourteen maize (*Zea mays* L.) inbred lines, including seven female parents (lines) and seven male parents (testers). These parental genotypes were selected based on their genetic diversity, contrasting phenotypic characteristics and breeding potential. A commercial hybrid, GAYMH-1, was included as the standard check for estimating standard heterosis. The details of the parental genotypes are presented in Table 1.

Development of Experimental Hybrids

Hybridization was carried out during the *rabi* season of 2023–24 at the Main Maize Research Station (MMRS), Anand Agricultural University, Godhra, Gujarat, India, following the Line × Tester mating design proposed by Kempthorne (1957). Seven female inbred lines were crossed with seven male testers to produce 49 F_1 hybrids.

Controlled pollination was performed using standard hand pollination techniques. Prior to anthesis, tassels of the designated male parents were covered with paper bags to prevent contamination, while tassels of female plants were removed before pollen shedding to avoid self-pollination. Ear shoots of female plants were also bagged before silk emergence. Fresh pollen collected from the respective male parent was manually applied to receptive silks between 08:00 and 10:30 hrs, after which the ears

Table 1 : List of maize genotypes.

S. no.	Genotypes	
	Lines	**Testers**
1.	IL-17-01	IGI-19-53
2.	IL-17-76	IL-17-79
3.	GYL-10	IGI-19-29
4.	LM-13-2	IL-14-39
5.	CML-296	IL-15-24
6.	IL-15-19	IL-12-17
7	IGI-19-09	IL-15-39
Check		
1.	GAYMH-1	

were re-bagged and tagged with the cross combination and pollination date. Mature crossed ears were harvested, dried and processed to obtain F_1 seed for evaluation.

Experimental Site and evaluation

The field evaluation was conducted during the *rabi* season of 2024-25 at the Main Maize Research Station, Anand Agricultural University, Godhra, Gujarat, India (22°45′ N latitude, 77°40′ E longitude, 119 m above mean sea level). The experimental site falls under the Middle Gujarat agro-climatic zone and is characterized by a semi-arid tropical climate with sandy loam soil of moderate fertility.

The experimental material consisted of 64 entries, including 49 F_1 hybrids, seven female parents, seven male parents and one commercial check hybrid (GAYMH-1). The trial was laid out in a Randomized Complete Block Design (RCBD) with three replications. Each genotype was grown in plots measuring 1.20 × 2.00 m with a spacing of 60 × 20 cm. All recommended agronomic and plant protection practices were followed uniformly throughout the crop season to ensure optimum crop growth and development.

Recording of observations

Observations were recorded on five randomly selected competitive plants from each plot for most quantitative traits. Data for days to 50% tasselling and 100 kernel weight were recorded on a plot basis.

The following characters were evaluated:

- Days to 50% tasselling
- Plant height (cm)
- Ear height (cm)
- Number of kernel row per cob
- 100 kernel weight (g)
- Kernel yield per plant (g)

Statistical analysis

The mean values recorded for each trait were subjected to analysis of variance (ANOVA) appropriate for a Randomized Complete Block Design following the procedure described by Panse and Sukhatme (1978) to determine the significance of genotypic differences.

Heterosis was estimated as heterobeltiosis (over the better parent) following Fonseca and Patterson (1968) and standard heterosis (over the commercial check) according to Meredith and Bridge (1972).

Combining ability analysis was carried out according to the Line × Tester method of Kempthorne (1957) to estimate general combining ability (GCA), specific combining ability (SCA) and their associated variance components. The relative importance of additive and non-additive gene action was assessed using GCA and SCA variances, and the significance of combining ability effects was tested using the corresponding standard errors and critical differences. All statistical analyses were performed using the software developed by the Department of Agricultural Statistics, Anand Agricultural University, Anand, Gujarat, India.

Results and Discussion

Analysis of variance

Analysis of variance (ANOVA) revealed highly significant differences among genotypes for all the six characters studied namely days to 50% tasselling, plant height, ear height, number of kernel row per cob, 100 kernel weight and kernel yield per plant (Table 2). The significant mean squares among parents, hybrids and their respective contrasts indicated the existence of substantial genetic variability in the experimental material and suggested ample scope for genetic improvement through

Table 2 : Analysis of variance for characters under study in maize.

Source of variation	Df	Days to 50% tasseling	Plant height	Ear height	Number of kernel row/cob	100 Kernel Weight	Kernel Yield/Plant
Replications	2	17.57	132.99	183.15	0.76	18.29	7.11
Genotypes (G)	63	40.70**	1354.09**	601.66**	2.69*	37.58**	913.35**
Parents (P)	13	45.62**	1716.39**	636.67**	2.70**	75.67**	1933.15**
Females (F)	6	30.99**	1994.48**	401.97**	3.04**	65.96**	2142.86**
Males (M)	6	62.41**	1708.79**	886.18**	2.41**	86.85**	1998.49**
Female *vs* Males	1	32.60**	93.56	547.81**	2.38**	66.88**	282.59
Hybrids (H)	48	33.79**	551.04**	414.47**	2.80**	26.58**	650.42**
Parents *vs* Hybrids	1	278.84**	30119.00**	8690.71**	0.34	42.41**	776.09**
Check *vs* Hybrids	1	70.41**	6425.50**	1042.71**	0.0047	65.30**	414.12**
Error	124	10.15	92.78	99.53	1.57	7.29	125.20

Where, *, ** indicate level of significance at 5% and 1%, respectively.

Table 3 : Magnitude of heterobeltiosis (HB) and standard heterosis (SH) for days to 50 % tasseling, plant height, ear height and number of kernel row per cob.

S. no.	Hybrids	Days to 50 % tasseling		Plant height		Ear Height		Number of kernel row/cob	
		HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)
1	IL-17-01 × IGI-19-53	-0.92	10.16**	25.00**	47.83**	10.93	31.82**	-4.19**	9.52**
2	IL-17-01 × IL-17-79	0.90	13.71**	5.40	45.43**	-3.50	25.33**	-12.50**	0.00
3	IL-17-01 × IGI-19-29	1.71	20.8**	15.89*	35.78**	3.82	23.38**	-12.50**	0.00
4	IL-17-01 × IL-14-39	-4.33	12.19**	0.28	31.76**	10.26	39.61**	-12.50**	0.00
5	IL-17-01 × IL-15-24	4.63	14.72**	4.74	22.71**	-5.47	12.34	-12.50**	0.00
6	IL-17-01 × IL-12-17	1.90	8.64**	3.96	26.36**	-9.23	14.95	-8.33**	4.76**
7	IL-17-01 × IL-15-39	6.49*	16.76**	11.23	31.54**	1.63	20.79*	-16.67**	-4.76**
8	IL-17-76 × IGI-19-53	-7.46**	7.11**	-5.03	31.03**	0.00	20.79*	-12.50**	0.00
9	IL-17-76 × IL-17-79	-10.23**	2.54	-3.18	33.58**	-6.00	22.08**	-4.19**	9.52**
10	IL-17-76 × IGI-19-29	-9.83**	7.11**	2.86	41.91**	11.50	44.82**	-12.50**	0.00
11	IL-17-76 × IL-14-39	-9.96**	5.59*	-1.32	36.13**	-1.53	24.69**	-12.50**	0.00
12	IL-17-76 × IL-15-24	-0.44	13.71**	-1.37	30.66**	1.08	22.08**	-8.33**	4.76**
13	IL-17-76 × IL-12-17	-7.61**	-1.51	-5.61	24.03**	-3.08	22.74**	-12.50**	0.00
14	IL-17-76 × IL-15-39	-11.41**	2.54	-12.70	20.45*	0.54	21.43**	-25.00**	-14.29**
15	GYL-10 × IGI-19-53	-11.12**	5.59*	-3.11	27.52**	18.93*	43.64**	-12.50**	0.00
16	GYL-10 × IL-17-79	-9.40**	7.62**	-5.75	20.73**	-15.50	9.74	-8.33**	4.76**
17	GYL-10 × IGI-19-29	-3.85	14.22**	-3.05	36.93**	-4.30	15.58	-4.19**	9.52**
18	GYL-10 × IL-14-39	-2.99	15.24**	-3.07	33.72**	-8.21	16.22*	-8.33**	4.76**
19	GYL-10 × IL-15-24	-14.96**	1.02	-4.71	28.53**	-8.06	11.05	-4.19**	9.52**
20	GYL-10 × IL-12-17	-10.68**	6.10*	-4.35	26.04**	5.64	33.77**	0.00	14.29**
21	GYL-10 × IL-15-39	-12.82**	3.56	-6.14	17.15*	-9.14	9.74	-8.33**	4.76**
22	LM-13-2 × IGI-19-53	-10.53**	3.56	2.79	31.69**	1.08	22.08**	-16.67**	-4.76**
23	LM-13-2 × IL-17-79	-11.39**	6.60**	-6.32	17.27*	-16.50*	8.44	-8.33**	4.76**
24	LM-13-2 × IGI-19-29	-17.30**	-0.49	-2.10	18.98*	0.54	21.43**	-4.19**	9.52**
25	LM-13-2 × IL-14-39	-12.66**	5.08	-2.71	28.25**	5.13	33.13**	-20.83**	-9.52**
26	LM-13-2 × IL-15-24	-11.81**	6.10*	-3.54	33.28**	-12.36	5.85	-20.83**	-9.52**
27	LM-13-2 × IL-12-17	-3.80	15.74**	-3.27	33.65**	-14.88	7.79	-16.67**	-4.76**
28	LM-13-2 × IL-15-39	-10.13**	8.13**	-7.66	15.26	-7.52	11.70	-8.33**	4.76**
29	CML-296 × IGI-19-53	-5.10	4.07	-6.46	32.12**	-24.19**	-8.45	-4.76**	-4.76**
30	CML-296 × IL-17-79	-4.63	4.57	-2.91	33.94**	-9.00	18.18*	-4.76**	-4.76**
31	CML-296 × IGI-19-29	-3.71	5.59*	-6.01	35.84**	-2.68	17.54*	4.76**	4.76**
32	CML-296 × IL-14-39	-3.24	6.10*	-6.41	32.20**	-6.67	18.18*	-4.76**	-4.76**
33	CML-296 × IL-15-24	-7.88**	1.02	-6.04	8.03	-18.29*	-1.31	4.76**	4.76**
34	CML-296 × IL-12-17	-5.10	4.07	-4.45	34.96**	-1.03	25.33**	0.00	0.00
35	CML-296 × IL-15-39	-7.40**	1.53	-2.70	18.25*	-18.29*	-1.31	0.00	0.00
36	IL-15-19 × IGI-19-53	-10.53**	3.56	-2.23	28.46**	-13.97	3.89	0.00	0.00
37	IL-15-19 × IL-17-79	-2.95	16.76**	-8.20	26.65**	-3.50	25.33**	9.52**	9.52**
38	IL-15-19 × IGI-19-29	-4.65	14.73**	-0.95	22.55**	-10.76	7.79	-4.76**	-4.76**
39	IL-15-19 × IL-14-39	-12.24**	5.59*	-7.49	39.80**	16.43*	47.41**	0.00	0.00
40	IL-15-19 × IL-15-24	-11.81**	6.10*	-7.65	36.50**	-1.50	27.91**	-19.05**	-19.05**
41	IL-15-19 × IL-12-17	-12.24**	5.59*	-3.95	26.20**	-9.23	14.95	0.00	0.00
42	IL-15-19 × IL-15-39	-5.48*	13.71**	-2.48	34.76**	0.52	27.27**	-4.76**	-4.76**
43	IGI-19-09 × IGI-19-53	-12.09**	7.11**	-3.06	43.50**	20.99*	46.10**	-12.50**	0.00

Table 3 continued...

Table 3 continued...

44	IGI-19-09 × IL-17-79	-11.66**	7.62**	-2.13	51.10**	1.50	31.82**	-12.50**	0.00
45	IGI-19-09 × IGI-19-29	-12.91**	6.10*	-2.33	28.53**	-1.08	19.48*	-12.50**	0.00
46	IGI-19-09 × IL-14-39	-12.91**	6.10*	-2.58	47.20**	28.21**	62.33**	-4.19**	9.52**
47	IGI-19-09 × IL-15-24	-15.41**	3.05	-9.60	30.66**	-1.00	28.57**	-8.33**	4.76**
48	IGI-19-09 × IL-12-17	-16.25**	2.04	-8.40	35.40**	9.75	38.98**	-25.00**	-14.29**
49	IGI-19-09 × IL-15-39	-12.91**	6.10*	-3.81	23.43**	2.69	24.02**	-20.83**	-9.52**
S.E.(Sij) ±		2.6		7.86		8.14		1.02	

Where, *, ** indicate level of significance at 5% and 1%, respectively.

hybrid breeding. The significant parents *vs.* hybrids contrast for almost all traits without number of kernel row per cob trait confirmed the presence of heterosis in the experimental population.

Further partitioning of variance showed that both female lines and testers contributed significantly to the observed variation for most of the traits, indicating that the selected parental lines possessed adequate genetic diversity. The relatively low error variance further demonstrated good experimental precision, thereby ensuring the reliability of the observed differences among genotypes.

The present findings are in close agreement with several recent studies which also reported highly significant differences among genotypes, parents, hybrids and line × tester components for grain yield and related traits. These studies attributed the observed variation to the presence of substantial genetic diversity among parental lines providing ample scope for effective selection and hybrid development (Hossain *et al.*, 2026; Vardhini *et al.*, 2024; Engida *et al.*, 2024 and Dharani *et al.*, 2024).

General Combining Ability (GCA)

Among the maturity traits, significant negative GCA effects for days to 50% tasselling were exhibited by CML-296 (-2.34**), IL-17-76 (-1.39*) and IGI-19-09 (-1.29*), while among the testers, IL-12-17 (-1.05) and IGI-19-53 (-1.01) were identified as desirable general combiners (Table 6). For this trait none of the testers exhibited significant GCA effects. This indicates that additive gene effects contributed by the testers were relatively small and environmental variation may have reduced the expression of these genetic differences under the present experimental conditions. The significant negative GCA effects observed in the female parents indicate their potential as donors of favourable additive alleles for earliness. These parents can be effectively utilized in breeding programmes to develop early maturing hybrids and populations through selection and hybridization.

For plant height, the female parents LM-13-2 (-7.73**), GYL-10 (-4.92**) and CML-296 (-4.04*) and the testers IL-15-39 (-11.8**) and IL-15-24 (-5.13**) exhibited significant negative GCA effects indicating their suitability for reducing plant stature (Table 6). The significant positive GCA effects of IL-14-39 (7.63**) and IGI-19-53 (6.16**) indicate their potential as good combiners for plant height and their taller stature is advantageous in crossing and hybrid seed production programmes because it promotes efficient pollen shedding and pollination. The significant negative GCA effects observed for these traits indicate the presence of favourable additive genes governing reduced plant height.

For ear height CML-296 (-10.4**) and LM-13-2 (-5.00**) among the lines and IL-15-24 (-5.95**) and IL-15-39 (-4.84**) among the testers recorded significant negative GCA effects (Table 6). In contrast, for number of kernel row per cob, GYL-10 (0.91**) among the female parents and IL-17-79 (0.44*) among the testers exhibited desirable positive GCA effects (Table 6). Lower ear placement contributes to improved plant stability and reduced lodging whereas a greater number of kernel row per cob increases sink capacity and yield potential. Therefore, these parents may be exploited in hybrid breeding programmes to simultaneously improve plant architecture and yield components through additive gene action.

For the economically important traits, IL-17-76 (2.03**) and LM-13-2 (2.03**) exhibited the highest positive GCA effects for 100 kernel weight while among the testers IL-14-39 (1.31**) and IL-15-39 (1.07*) were identified as good general combiners.

For kernel yield per plant, IL-17-76 (7.96**) emerged as the best general combiner followed by IL-15-19 (5.91**) and IGI-19-09 (5.29*) whereas IL-14-39 (4.86*) was the best tester (Table 6). The superior GCA effects observed for kernel weight and grain yield indicate that these parents possess favourable additive alleles for productivity and can serve as valuable donor parents in future hybrid breeding programmes. Their consistent performance also suggests good breeding value for

Table 4 : Magnitude of heterobeltiosis (HB) and standard heterosis (SH) for 100 kernel weight and kernel yield per plant.

S. no.	Hybrids	100 kernel weight		Kernel yield/plant	
		HB (%)	SH (%)	HB (%)	SH (%)
1	IL-17-01 × IGI-19-53	-21.43**	-27.46**	-23.78*	-14.40
2	IL-17-01 × IL-17-79	-7.14**	-14.28**	-26.57**	-17.54
3	IL-17-01 × IGI-19-29	6.34**	-7.68**	-12.59	-1.83
4	IL-17-01 × IL-14-39	8.88**	-5.47**	-17.48	-7.32
5	IL-17-01 × IL-15-24	10.14**	-4.38*	-36.83**	-29.06**
6	IL-17-01 × IL-12-17	10.14**	-4.38*	-7.92	3.41
7	IL-17-01 × IL-15-39	-40.00**	-30.76**	-33.57**	-25.40**
8	IL-17-76 × IGI-19-53	-14.29**	-20.87**	-21.86*	-16.76
9	IL-17-76 × IL-17-79	-9.54**	-16.48**	-14.18	-9.68
10	IL-17-76 × IGI-19-29	13.32**	-6.59**	38.24**	15.44
11	IL-17-76 × IL-14-39	6.47**	-9.89**	-2.39	-3.93
12	IL-17-76 × IL-15-24	5.32*	-13.19**	11.92	-6.54
13	IL-17-76 × IL-12-17	17.32**	-3.30	21.00*	1.05
14	IL-17-76 × IL-15-39	-5.71*	8.80**	16.97	-0.78
15	GYL-10 × IGI-19-53	-2.39	-9.89**	-10.32	-4.44
16	GYL-10 × IL-17-79	-16.68**	-23.08**	-24.87**	-20.95*
17	GYL-10 × IGI-19-29	11.27**	-24.17**	42.72**	-9.96
18	GYL-10 × IL-14-39	-6.51**	-20.87**	1.33	-0.26
19	GYL-10 × IL-15-24	-30.13**	-43.95**	-22.67*	-39.28**
20	GYL-10 × IL-12-17	24.16**	-20.87**	50.36**	3.14
21	GYL-10 × IL-15-39	-25.71**	-14.28**	12.04	-4.97
22	LM-13-2 × IGI-19-53	-10.71**	-17.57**	-17.19	-11.78
23	LM-13-2 × IL-17-79	17.86**	8.80**	-16.42	-12.05
24	LM-13-2 × IGI-19-29	11.27**	-24.17**	17.06	-22.79*
25	LM-13-2 × IL-14-39	12.97**	-4.38*	-22.07*	-23.31*
26	LM-13-2 × IL-15-24	16.44**	-6.59**	15.33	-9.42
27	LM-13-2 × IL-12-17	41.03**	-13.19**	35.89**	-6.80
28	LM-13-2 × IL-15-39	-17.14**	-4.38*	9.57	-7.07
29	CML-296 × IGI-19-53	-16.68**	-23.08**	-24.32**	-19.38*
30	CML-296 × IL-17-79	-9.54**	-16.48**	-9.20	-4.44
31	CML-296 × IGI-19-29	10.13**	-16.48**	3.83	-14.93
32	CML-296 × IL-14-39	6.47**	-9.89**	-16.48	-17.81
33	CML-296 × IL-15-24	0.00	-19.78**	7.35	-12.05
34	CML-296 × IL-12-17	1.43	-23.08**	4.16	-14.68
35	CML-296 × IL-15-39	-27.63**	-16.48**	-5.56	-19.90*
36	IL-15-19 × IGI-19-53	-5.96**	-13.19**	7.12	14.12
37	IL-15-19 × IL-17-79	-21.43**	-27.46**	-19.65*	-15.46
38	IL-15-19 × IGI-19-29	-5.25*	-20.87**	-0.78	-0.26
39	IL-15-19 × IL-14-39	5.18*	-10.98**	22.35*	20.40*
40	IL-15-19 × IL-15-24	-9.20**	-24.17**	-27.87**	-27.49**
41	IL-15-19 × IL-12-17	-13.15**	-27.46**	-20.57*	-20.17*
42	IL-15-19 × IL-15-39	-30.48**	-19.78**	-4.16	-3.66
43	IGI-19-09 × IGI-19-53	-21.18**	-26.37**	-6.60	7.60
44	IGI-19-09 × IL-17-79	-4.69*	-10.98**	-17.95	-5.50

Table 4 continued...

developing high-yielding maize hybrids.

Similar results have been reported by recent researchers who identified maize inbred lines with significant positive GCA effects for grain yield and concluded that these parents are efficient donors of favourable additive genes for improving productivity through hybrid breeding (Engida *et al.*, 2024; Vardhini *et al.*, 2024; Hossain *et al.*, 2026 and Dharani *et al.*, 2024).

Specific Combining Ability (SCA)

For days to 50% tasselling, the hybrids LM-13-2 × IGI-19-29 (-6.04**), GYL-10 × IL-15-24 (-3.76**) and IL-17-76 × IL-12-17 (-3.42**) exhibited significant negative SCA effects (Table 7). Similarly, significant negative SCA effects for plant height were observed in CML-296 × IL-15-24 (-25.13**), LM-13-2 × IL-17-79 (-15.70**), IGI-19-09 × IGI-19-29 (-14.33**) and GYL-10 × IL-17-79 (-13.25**) (Table 7). These hybrids exhibited favourable non-additive gene interactions for earliness and reduced plant height. Such combinations are promising for exploiting heterosis to develop early flowering, lodging-resistant hybrids with improved adaptability under diverse production environments.

For ear height, the crosses CML-296 × IGI-19-53 (-16.36**), GYL-10 × IL-14-39 (-13.98**), IGI-19-09 × IGI-19-29 (-13.65**) and IL-17-76 × IL-14-39 (-11.50**) recorded significant negative SCA effects (Table 7). For number of kernel row per cob, positive SCA effects were observed in LM-13-2 × IL-15-39 (1.37*), IL-15-19 × IL-17-79 (1.28*), LM-13-2 × IGI-19-29 (1.18*), IL-17-01 × IGI-19-53 (1.18*) and GYL-10 × IL-12-17 (1.09*) (Table 7). The observed SCA effects indicate that these hybrid combinations possess favourable dominance and epistatic interactions governing plant architecture and kernel row development. These crosses may therefore be useful for improving both structural stability and sink capacity in future hybrid development programmes.

For 100 kernel weight, the highest positive SCA effects were recorded by GYL-10 × IGI-19-53 (5.12**), followed by LM-13-2 × IL-17-79 (4.97**), IL-17-76 × IL-15-39 (4.26**) and IL-17-01 × IL-15-24 (3.78**) (Table 7).

Table 4 continued...

45	IGI-19-09 × IGI-19-29	-4.69*	-10.98**	-24.09**	-12.57
46	IGI-19-09 × IL-14-39	-11.75**	-17.57**	-18.41*	-6.01
47	IGI-19-09 × IL-15-24	-14.12**	-19.78**	-18.64*	-6.28
48	IGI-19-09 × IL-12-17	-17.65**	-23.08**	-24.99**	-13.62
49	IGI-19-09 × IL-15-39	-19.06**	-6.59*	-12.73	0.53
S.E.(Sij) ±		2.20		9.13	

Where, *, ** indicate level of significance at 5% and 1%, respectively.

(20.23**), IL-17-01 × IL-12-17 (17.95**), CML-296 × IL-17-79 (16.85**) and LM-13-2 × IL-15-24 (16.80**) (Table 7). The high positive SCA effects for grain weight and kernel yield indicate the predominance of non-additive gene action for these traits. These hybrid combinations can be directly exploited in hybrid breeding programmes and should be further evaluated

Table 5 : Analysis of combining ability and variance components for different characters in maize.

Source of variation	df	Days to 50% tasseling	Plant height	Ear height	Number of kernel row/cob	100 Kernel weight	Kernel yield/plant
Replications	2	37.14**	177.95**	469.17**	0.73	23.04**	6.42**
Females	6	102.23**	809.95**	1023.25**	4.05**	56.15**	804.83**
Males	6	18.91**	969.19**	628.81**	2.08	50.52**	743.94**
Female × Male	36	24.86**	438.19**	277.28**	2.71**	22.66**	609.09**
Error	96	9.83	100.77	86.85	1.54	7.54	130.91

*, ** indicate level of significance at 5% and 1%, respectively.

Table 6 : Estimation of general combining ability effect associated with each parent for various.

Parents	Days to 50 % tasseling		Plant height		Ear height		Number of kernel row/cob		100 kernel weight		Kernel yield/plant	
Lines												
IL-17-01	4.23**	P	5.99**	P	1.82	A	0.15	A	0.6	A	-4.95*	P
IL-17-76	-1.39*	G	0.78	A	3.09	A	-0.04	A	2.03**	G	7.96**	G
GYL-10	0.14	A	-4.92**	G	-1.65	A	0.91**	A	-2.12**	A	-2.14	A
LM-13-2	-0.67	A	-7.73**	G	-5.00**	G	-0.23	A	2.03**	G	-5.14*	P
CML-296	-2.34**	G	-4.04*	G	-10.4**	G	-0.14	A	-0.73	A	-6.95**	P
IL-15-19	1.33*	P	0.21	A	0.16	A	-0.42	A	-1.54**	P	5.91**	G
IGI-19-09	-1.29*	G	9.73**	P	11.98**	P	-0.23	A	-0.26	A	5.29*	G
Testers												
IGI-19-53	-1.01	A	6.16**	G	0.81	A	-0.04	A	-1.31**	P	3.63	A
IL-17-79	0.71	A	3.2	A	-1.51	A	0.44*	G	0.36	A	-3.76	A
IGI-19-29	1.52**	P	1.53	A	-0.4	A	0.34	A	-0.12	A	3.29	A
IL-14-39	0.37	A	7.63**	G	10.79**	P	-0.04	A	1.31**	A	4.86*	G
IL-15-24	-0.58	A	-5.13**	P	-5.95**	G	-0.14	A	-1.02*	P	-11.85**	P
IL-12-17	-1.05	A	-1.59	A	1.11	A	-0.04	A	-0.31	A	3.15	A
IL-15-39	0.04	A	-11.8**	P	-4.84**	G	-0.52*	A	1.07*	A	0.67	A
S.E. (gi)	0.56		1.79		1.66		0.22		0.49		2.04	

*, ** indicate level of significance at 5% and 1%, respectively

G= Good specific combiner, A = Average specific combiner, P = Poor specific combiner.

For kernel yield per plant, IL-15-19 × IL-14-39 (27.04**) exhibited the highest SCA effect followed by IL-15-19 × IGI-19-53 (20.28**), IL-17-76 × IGI-19-29 across locations to assess their yield stability and commercial potential.

The present findings are in accordance with recent reports indicating that maize hybrids exhibiting high positive SCA effects for kernel yield are primarily governed by non-additive gene action and possess high heterotic potential. Such cross combinations are considered promising candidates for hybrid breeding and require further multi location evaluation to identify stable and commercially exploitable hybrids (Engida *et al*., 2024; Vardhini *et al*., 2024; Dharani *et al*., 2024; Goud *et al*., 2025; Chaurasia *et al*., 2025 and Hossain *et al*., 2026).

Heterosis

Negative heterosis is desirable for days to 50% tasselling trait because it indicates earliness. The highest significant negative heterobeltiosis was recorded by LM-13-2 × IGI-19-29 (-17.30%) followed by IGI-19-09 × IL-12-17 (-16.25%), IGI-19-09 × IL-15-24 (-15.41%), GYL-10 × IL-15-24 (-14.96%), IL-15-19 × IL-14-39 (-12.24%) and IGI-19-09 × IL-15-39 (-12.91%) (Table 3). Among the hybrids, only IL-17-76 × IL-12-17 (-1.51%) exhibited negative standard heterosis over the commercial check, whereas the remaining hybrids showed positive standard heterosis. The significant negative heterobeltiosis observed in these hybrids indicates the presence of favourable non-additive gene action for earliness. Such hybrids are valuable for developing early maturing cultivars suitable for multiple cropping systems, moisture stress conditions and regions with shorter growing seasons.

For plant height, the highest heterobeltiosis was recorded by IL-17-01 × IGI-19-53 (25.00%) followed by IL-17-01 × IGI-19-29 (15.89%), IL-17-01 × IL-17-79 (5.40%) and IL-17-76 × IL-15-39 (12.70%). The highest standard heterosis was exhibited by IGI-19-09 × IL-17-79 (51.10%) followed by IGI-19-09 × IL-14-39 (47.20%), IL-17-01 × IGI-19-53 (47.83%), IL-17-76 × IGI-19-29 (41.91%) and IL-15-19 × IL-14-39 (39.80%) (Table 3). Positive heterosis for plant height indicates increased hybrid vigour and vegetative growth. Although, taller plants may produce greater biomass and pollen, hybrids with moderate plant height are generally preferred in commercial breeding programmes to reduce lodging and improve harvestability.

The highest positive heterobeltiosis for ear height was observed in IGI-19-09 × IL-14-39 (28.21%) followed by IGI-19-09 × IGI-19-53 (20.99%), GYL-10 × IGI-19-53 (18.93%), IL-15-19 × IL-14-39 (16.43%) and IL-17-76 × IGI-19-29 (11.50%). The same hybrid, IGI-19-09 × IL-14-39 also recorded the highest standard heterosis (62.33%) followed by IGI-19-09 × IGI-19-53 (46.10%), IL-17-76 × IGI-19-29 (44.82%), GYL-10 × IGI-19-53 (43.64%) and IL-15-19 × IL-14-39 (47.41%) (Table 3). The expression of positive heterosis for ear height reflects enhanced vegetative vigour. However, excessively high ear placement may increase lodging susceptibility. Therefore, hybrids with optimum ear height and superior grain yield should be preferred for further breeding programmes.

The highest heterobeltiosis for number of kernel row per cob was recorded by IL-15-19 × IL-17-79 (9.52%) whereas CML-296 × IGI-19-29 and CML-296 × IL-15-24 recorded 4.76% heterobeltiosis. For standard heterosis, the highest value (14.29 %) was observed in GYL-10 × IL-12-17 followed by IL-17-01 × IGI-19-53, IL-17-76 × IL-17-79, GYL-10 × IGI-19-29 and LM-13-2 × IGI-19-29 each exhibiting 9.52% standard heterosis (Table 3). Positive heterosis for kernel row per cob indicates improved sink capacity, which contributes directly to higher grain yield. Hybrids exhibiting superior heterosis for this trait can therefore be utilized for improving yield potential in future hybrid breeding programmes.

The highest heterobeltiosis for 100 kernel weight was recorded by LM-13-2 × IL-12-17 (41.03%) followed by GYL-10 × IL-12-17 (24.16%), LM-13-2 × IL-17-79 (17.86%), IL-17-76 × IL-12-17 (17.32%) and LM-13-2 × IL-15-24 (16.44%) (Table 4). The highest standard heterosis (8.80%) was recorded by IL-17-76 × IL-15-39 and LM-13-2 × IL-17-79 followed by IL-17-01 × IL-15-24 (4.38%) and IL-17-01 × IL-12-17 (4.38%). The high positive heterosis for kernel weight indicates improved grain filling and assimilate partitioning in these hybrids. Such combinations may be useful for developing hybrids with bold grains and enhanced marketable yield.

Kernel yield per plant exhibited considerable heterosis among the hybrids. The highest heterobeltiosis was recorded by GYL-10 × IL-12-17 (50.36%) followed by GYL-10 × IGI-19-29 (42.72%), IL-17-76 × IGI-19-29 (38.24%), LM-13-2 × IL-12-17 (35.89%), IL-15-19 × IL-14-39 (22.35%), IL-17-76 × IL-12-17 (21.00%) and LM-13-2 × IGI-19-29 (17.06%) (Table 4). For standard heterosis, IL-15-19 × IL-14-39 (20.40%) recorded the highest superiority over the commercial check, followed by IL-17-76 × IGI-19-29 (15.44%), IL-15-19 × IGI-19-53 (14.12%), IGI-19-09 × IGI-19-53 (7.60%) and IL-17-01 × IL-12-17 (3.41%). The substantial positive heterosis observed for kernel yield confirms the importance of non-additive gene action in the inheritance of grain yield. Hybrids such as IL-15-19 × IL-14-39, IL-17-76 × IGI-19-29 and GYL-10 × IL-12-17, which exhibited high heterobeltiosis and/or standard heterosis are promising candidates for multi-location evaluation and may be

Table 7 : Estimates of specific combining ability effects associated with each hybrid for various characters.

Hybrid/crosses	Days to 50% tasseling		Plant height		Ear height		Number of kernel row/cob		100 kernels weight		Kernel yield/plant	
IL-17-01 × IGI-19-53	-1.42	A	14.33**	P	5.86	A	1.18*	G	-2.93*	P	-5.20	A
IL-17-01× IL-17-79	-0.80	A	13.40**	P	2.62	A	-0.63	A	-0.60	A	-1.82	A
IL-17-01 × IGI-19-29	3.05*	P	0.41	A	-0.16	A	-0.53	A	1.88	A	11.14*	G
IL-17-01× IL-14-39	-1.47	A	-11.81**	G	2.54	A	-0.15	A	1.12	A	2.56	A
IL-17-01× IL-15-24	1.15	A	-12.83**	G	-4.05	A	-0.05	A	3.78**	G	-8.39	A
IL-17-01× IL-12-17	-2.37	A	-10.81*	G	-8.89*	G	0.52	A	3.07*	G	17.95**	G
IL-17-01 × IL-15-39	1.86	A	7.30	A	2.07	A	-0.34	A	-6.31**	P	-16.24**	P
IL-17-76× IGI-19-53	2.20	A	-6.24	G	-4.85	A	0.04	A	-2.36	A	-21.10**	P
IL-17-76× IL-17-79	-2.52	A	0.61	A	-1.43	A	0.90	A	-2.69*	P	-4.72	A
IL-17-76× IGI-19-29	-0.33	A	14.61**	P	16.91**	P	-0.34	A	0.78	A	20.23**	G
IL-17-76× IL-14-39	-0.18	A	0.07	A	-11.50**	G	0.04	A	-1.65	A	-6.01	A
IL-17-76× IL-15-24	6.10**	P	4.49	A	3.02	A	0.80	A	-0.31	A	7.37	A
IL-17-76× IL-12-17	-3.42*	G	-9.16*	G	-3.49	A	0.04	A	1.97	A	2.04	A
IL-17-76× IL-15-39	-1.85	A	-4.38	A	1.35	A	-1.48**	P	4.26**	G	2.18	A
GYL-10 × IGI-19-53	-0.33	A	-5.87	A	19.45**	P	-0.91	A	5.12**	G	4.66	A
GYL-10 × IL-17-79	-0.71	A	-13.25**	G	-7.24	A	-0.72	A	-0.55	A	-8.96	A
GYL-10 × IGI-19-29	2.82*	P	14.10**	P	-3.35	A	0.04	A	-0.41	A	-2.01	A
GYL-10 × IL-14-39	4.63**	P	2.10	A	-13.98**	G	-0.24	A	-0.84	A	8.76	A
GYL-10× IL-15-24	-3.76**	G	6.97	A	-1.68	A	0.52	A	-5.50**	P	-24.20**	P
GYL-10 × IL-12-17	0.05	A	-0.37	A	10.70**	P	1.09*	G	0.78	A	14.80**	G
GYL-10 × IL-15-39	-2.71	A	-3.68	A	-3.90	A	0.23	A	1.40	A	6.95	A
LM-13-2 × IGI-19-53	-0.85	A	3.27	A	4.35	A	-0.44	A	-1.36	A	-1.67	A
LM-13-2 × IL-17-79	-0.56	A	-15.70**	G	-5.00	A	0.42	A	4.97**	G	5.37	A
LM-13-2 × IGI-19-29	-6.04**	G	-11.43*	G	5.00	A	1.18*	G	-4.55**	P	-15.34**	P
LM-13-2 × IL-14-39	-1.23	A	-3.42	A	3.81	A	-1.10*	P	0.02	A	-17.58**	P
LM-13-2 × IL-15-24	0.39	A	17.00**	P	-4.44	A	-1.01	A	1.69	A	16.80**	G
LM-13-2 × IL-12-17	7.20**	P	14.02**	P	-4.84	A	-0.44	A	-1.03	A	5.14	A
LM-13-2 × IL-15-39	1.10	A	-3.76	A	1.11	A	1.37*	G	0.26	A	7.28	A
CML-296 × IGI-19-53	1.15	A	0.25	A	-16.36**	G	-0.53	A	-0.27	A	-9.53	A
CML-296 × IL-17-79	-0.23	A	5.99	A	8.73*	P	-1.01	A	0.07	A	16.85**	G
CML-296 × IGI-19-29	-0.37	A	10.56*	P	7.07	A	0.42	A	0.54	A	-3.53	A
CML-296 × IL-14-39	1.10	A	-1.11	A	-3.57	A	-0.53	A	1.12	A	-8.77	A
CML-296 × IL-15-24	-1.28	A	-25.13**	G	-3.49	A	0.90	A	0.45	A	15.28**	G
CML-296 × IL-12-17	1.20	A	12.33**	P	12.22**	P	0.14	A	-1.27	A	-3.05	A
CML-296 × IL-15-39	-1.56	A	-2.89	A	-4.60	A	0.61	A	-0.65	A	-7.24	A
IL-15-19 × IGI-19-53	-2.85*	G	-9.56*	G	-16.36**	G	0.42	A	3.54**	G	20.28**	G
IL-15-19× IL-17-79	4.10**	P	-9.38*	G	4.29	A	1.28*	G	-2.46*	P	-10.01*	P
IL-15-19 × IGI-19-29	1.96	A	-13.92**	G	-11.82**	G	-0.63	A	0.02	A	2.88	A
IL-15-19× IL-14-39	-2.90*	G	6.19	A	10.88**	P	0.42	A	1.59	A	27.04**	G
IL-15-19× IL-15-24	-1.61	A	13.95**	P	10.95**	P	-2.15**	P	-0.07	A	-17.24**	P
IL-15-19× IL-12-17	-1.47	A	-5.25	A	-7.22	A	0.42	A	-1.79	A	-22.91**	P
IL-15-19× IL-15-39	2.77*	P	17.97**	P	9.29*	P	0.23	A	-0.84	A	0.56	A
IGI-19-09 × IGI-19-53	2.10	A	3.81	A	7.92	A	0.23	A	-1.74	A	12.56*	G
IGI-19-09 × IL-17-79	0.72	A	18.33**	P	-1.98	A	-0.24	A	1.26	A	3.28	A

Table 7 continued...

Table 7 continued...

IGI-19-09 × IGI-19-29	-1.09	A	-14.33**	G	-13.65**	G	-0.15	A	1.73	A	-12.77*	P
IGI-19-09 × IL-14-39	0.05	A	7.97	P	11.83**	P	1.56**	G	-1.36	A	-6.01	A
IGI-19-09 × IL-15-24	-0.99	A	-4.46	A	-0.31	A	0.99	A	-0.03	A	10.37*	G
IGI-19-09 × IL-12-17	-1.18	A	-0.77	A	1.51	A	-1.77*	P	-1.74	A	-13.96**	P
IGI-19-09 × IL-15-39	0.39	A	-10.55*	G	-5.31	A	-0.63	A	1.88	A	6.52	A
S.E.(Sij) ±	1.37		4.38		4.07		0.54		1.20		4.99	

*, ** indicate level of significance at 5% and 1%, respectively

G= Good specific combiner, A = Average specific combiner, P = Poor specific combiner.

considered for commercial hybrid development after confirming their yield stability across environments.

The present results corroborate recent reports that maize hybrids exhibiting high heterobeltiosis and standard heterosis for kernel yield possess superior hybrid vigour and are promising candidates for commercial exploitation. Such hybrids should be evaluated across multiple environments to confirm their stability and adaptability before release (Chaurasia *et al.*, 2025; Goud *et al.*, 2025 and Hossain *et al.*, 2026).

Conclusion

The present investigation revealed the existence of substantial genetic variability among the parental lines and their hybrids for all the traits studied indicating good scope for genetic improvement through hybrid breeding. Significant GCA and SCA effects demonstrated the importance of both additive and non-additive gene actions in controlling the inheritance of yield and its associated traits. Among the parents, IL-17-76, IL-15-19 and IGI-19-09 were identified as superior general combiners for kernel yield per plant while IL-14-39 emerged as the best tester suggesting their potential as valuable donor parents in future maize improvement programmes. Among the hybrids, IL-15-19 × IL-14-39 (G × G), IL-17-76 × IGI-19-29 (G × A), IL-15-19 × IGI-19-53 (G × A) and IL-17-01 × IL-12-17 (P × A) exhibited desirable specific combining ability and high heterotic performance for kernel yield reflecting the predominance of non-additive gene action.

In particular, IL-15-19 × IL-14-39 showed the highest standard heterosis over the commercial check whereas GYL-10 × IL-12-17 recorded the highest heterobeltiosis for kernel yield per plant. These hybrids possess considerable potential for commercial exploitation; however, their performance should be validated through multi location and multi season evaluations to confirm yield stability and adaptability before their recommendation for hybrid development programmes.

Author's contribution

Mehulkumar Parmar: Investigation, Data collection and Writing - original draft. P. K. Parmar: Supervision, Conceptualization, Methodology. G. B. Patil: Supervision. M. B. Patel: Supervision, Conceptualization, Methodology. D. J. Parmar: Data analysis. Bhavesh Thakor: Writing - original draft, Investigation and Data collection.

Conflicts of interest

There is no conflict of interest

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