



Diverse Parents Revealed Heterotic Combination in Maize (*Zea mays* L.) for Yield and its Contributing Traits

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ABSTRACT

The experiment was conducted during the late *kharif* season (September to December), 2025 at the Main Maize Research Station, Godhra, Gujarat, India to evaluate the performance and heterosis of maize hybrids. The experimental material comprised six lines and six testers, which were crossed in a Line×Tester mating design to produce thirty-six hybrids. These hybrids, along with their twelve parents and a standard check hybrid GAYMH 3, were evaluated in a Randomized Complete Block Design (RBD) with three replications under field conditions at the same location. Observations were recorded for fourteen characters, including yield and quality traits. The analysis of variance indicated highly significant differences among genotypes for all traits, revealing considerable genetic variability. Among the hybrids, IL-17-39×IL-14-34, IL-17-77×IL-17-55 and IL-14-24×IL-15-19 exhibited the highest standard heterosis and heterobeltiosis for kernel yield, along with superior performance in cob girth, cob length, cob weight, shelling percentage, 100-kernel weight and protein content. Hierarchical cluster analysis using Euclidean distance and Ward's D2 method showed that the parents of these crosses belonged to genetically diverse clusters, confirming that greater genetic divergence enhances heterosis through effective genetic complementation. Overall, the lines IL-17-39, IL-17-77 and IL-14-24, and testers IL-14-34, IL-17-55 and IL-15-19, along with the identified hybrids, demonstrated promising yield potential. Further studies are needed to evaluate their stability and adaptability across different environments.

KEYWORDS: Line×tester, heterobeltiosis, standard heterosis, euclidean distance, ward's D2

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Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, author have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

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1. INTRODUCTION

Maize is one of the most widely cultivated cereal crops globally and serves as a primary staple food in many developing countries (Wang and Zhang, 2024). Since 2010, its output has increased by 46%, the fastest growth among major cereals, due to its wide use in food, animal feed and biofuel production (Anonymous, 2024). In the year 2024–2025 in India, maize is cultivated in an area of 12.01 million ha with the production of 42.28 mt and an average productivity of 3518 kg ha⁻¹. Maize is the third most important cereal crop in India after rice and wheat. The three largest maize-producing states are Madhya Pradesh, Karnataka and Bihar (Anonymous, 2025a). The total maize occupying area in Gujarat is 4.28 lakh ha; production is 8.21 lakh tonnes and 1917.30 kg ha⁻¹ average productivity (Anonymous, 2025b). Although this is below the national average, productivity in Gujarat has been steadily improving. Maize cultivation is mainly concentrated in the eleventh districts, including Panchmahal, Dahod, Chhota Udepur, Mahisagar, Aravalli, Banaskantha, Sabarkantha, Vadodara, Narmada and Tapi. The low productivity in these areas is due to the utilization of low-yielding landraces and low-input management. Hybrid maize is one of the major achievements in modern agriculture, playing an important role in global food security and productivity. The variety was developed using heterosis or hybrid vigor, which gives better performance than the parent lines (Flint et al., 2009). Hybrid maize generally provides higher yields, more uniform plants, stronger resistance to diseases, and better tolerance to stress compared to open-pollinated varieties or inbred lines (Hallauer et al., 2010). Inbred lines usually show reduced strength due to inbreeding depression, but when two diverse inbred lines are crossed, the F₁ hybrid shows significant improvements, especially in grain yield, which can be 15–50% higher than the better parent. Because of these advantages, hybrid seed production has become an integral component of commercial maize cultivation worldwide (Duvick, 2001). Genetic variability is a prerequisite to initiate a breeding programme and operate selection (Borkhatariya et al., 2023; Sondarava et al., 2025). Genetically diverse parents are essential for exploiting heterosis in maize, as greater genetic divergence between parental lines generally leads to higher hybrid vigor and improved yield performance (Shull, 1908; Falconer, 1960; Mian and Bhal, 1989). The use of diverse inbred lines enhances the probability of favorable dominant and epistatic gene interactions, which are the genetic basis of heterosis in maize (Hallauer et al., 2010). Many plant breeders (Mukiti et al., 2025) have widely employed hierarchical clustering using Ward's D2 method (Ward, 1963) in combination with Euclidean distance to compute genetic dissimilarity among maize genotypes, as this approach effectively minimizes

within-cluster variance and provides clear grouping of genetically diverse parents. Heterosis, also known as hybrid vigour or outbreeding enhancement, refers to the phenomenon in which F₁ hybrids produced by crossing two genetically different gametes or individuals exhibit increased or decreased vigour compared to their parents. (Shull, 1908). In agriculture, heterosis is widely used to develop high-yielding hybrids; several recent studies have emphasized the importance of heterosis breeding in crop improvement, particularly for yield enhancement and stability (Bhatla et al., 2025). Heterosis is classified into three types: average heterosis (over the mid-parent), heterobeltiosis (over the better parent) (Fonseca and Patterson, 1968), and standard heterosis (over a standard check) (Meredith and Bridge, 1972). In this context, L×T analysis (Kempthorne, 1957) has been widely used for the evaluation of inbred lines by crossing them with testers. The present investigation was undertaken to identify genetically diverse parents and to estimate the magnitude of heterobeltiosis and standard heterosis for yield and related traits in maize, to select superior hybrids

2. MATERIALS AND METHODS

2.1. Experimental sites

The experiment was conducted at the Main Maize Research Station, Anand Agricultural University, Godhra, Gujarat, India, during *kharif*, 2022 for making crosses and developing hybrids. The resulting hybrids, along with their parental lines, were stored in cold storage at MMRS, Godhra and evaluated during late *kharif* (September to December, 2025). The Main Maize Research Station, AAU, Godhra, is situated within Agro-climatic zone-III, which corresponds to Middle Gujarat. In terms of geographical coordinates, Godhra is positioned at a latitude of 22° 45' North and a longitude of 77° 40' East, with an elevation of 119 m above mean sea level.

2.2. Experimental materials

The experimental material comprised a total of 12 maize inbred lines used as parental genotypes. Among these, six were designated as female (lines), while the remaining six served as male (testers). All experiments were conducted in a Randomized Complete Block Design (RCBD) with three replications. Each genotype was planted in two rows of 3.0 m length, spaced 60 cm apart with a plant-to-plant spacing of 20 cm. Recommended agronomic and plant protection practices were followed to ensure the successful raising of the crop (Table 1).

2.3. Observations recorded

Observations on different quantitative characters as well as qualitative characters were recorded in each plot on five randomly tagged plants, except for days to 50% tasseling,

Table 1: List of maize parental lines used in the experiment and their sources

Sr. No.	Genotypes	Source
Females (Lines)		
1.	IL-14-24	Main maize research station,
2.	IGI-19-25	Godhra, Godhra
3.	IL-17-77	
4.	IL-17-01	
5.	IL-17-39	
6.	IL-17-81	
Males (Testers)		
1.	IL-17-73	Main maize research station,
2.	IL-15-19	Godhra, Godhra
3.	IGI-19-09	
4.	IL-14-34	
5.	IL-15-23	
6.	IL-17-55	
Standard check		
1.	GAYMH-3	Main maize research station,
		Godhra, Godhra

days to 50% silking, and days to maturity, which will be recorded on a per-plot basis. To perform statistical analysis, the mean values of these traits were calculated from the recorded observations. Observations were recorded on Fourteen different characters of maize i.e. days to 50% tasselling, days to 50% silking, days to maturity, plant height (cm), ear height (cm), cob girth (cm), cob length (cm), cob weight (g), number of kernel row cob⁻¹, number of kernel row⁻¹, shelling (%), 100 kernels weight (g), kernel yield plant⁻¹ (g) and protein content (%).

2.4. Statistical analysis

The replication-wise mean values of all the genotypes for different characters were subjected to statistical analysis. Genetic divergence among maize genotypes was assessed using hierarchical cluster analysis. The data for all quantitative traits were standardized (mean=0, variance=1) to remove scale effects. The dissimilarity matrix was computed using Euclidean distance, and the resulting matrix was subjected to hierarchical clustering using Ward's D2 method, which minimizes within-cluster variance (Ward, 1963; Murtagh and Legendre, 2014). The analysis was performed using the hclust function in R software and the dendrogram was used to classify genotypes into distinct clusters for identifying genetically diverse parents.

In the present study, heterosis was estimated over a better parent and standard check hybrid (GAYCH-3), referred to

as heterobeltiosis (HB) and standard heterosis (SH).

Heterobeltiosis expressed as a percentage increase or decrease of the F₁ hybrid over the better parent and was calculated according to the method of Fonseca and Patterson (1968).

$$\text{Heterobeltiosis (\%)} = \frac{F_1 - \overline{BP}}{\overline{BP}} \times 100$$

Where,

F₁ = Mean performance of F₁

BP = Mean value of better parent for respective cross-combination

The test of significance of heterobeltiosis was carried out using the formula proposed by Turner (1953).

$$t = \frac{F_1 - \overline{BP}}{S.E.(\overline{F_1 - BP})} \text{ where, } S.E. \overline{F_1 - BP} = \sqrt{\frac{2MSE}{r}}$$

The calculated 't' values were compared with the Table 't' values at error degrees of freedom for their significance at 0.05 and 0.01 levels of probability.

Standard heterosis is expressed as the percentage increase or decrease of an F₁ hybrid over a standard check and is calculated according to the procedure described by Meredith and Bridge (1972).

$$\text{Standard heterosis (\%)} = \frac{F_1 - \overline{SC}}{\overline{SC}} \times 100$$

Where,

F₁ = Mean performance of F₁

SC = Mean value of standard check hybrid

The test of significance of standard heterosis was carried out using the formula proposed by Turner (1953).

$$t = \frac{F_1 - \overline{SC}}{S.E.(\overline{F_1 - SC})} \text{ where, } S.E. \overline{F_1 - SC} = \sqrt{\frac{2MSE}{r}}$$

The calculated 't' values were compared with the Table 't' values at error degrees of freedom for their significance at 5% and 1% levels of probability.

3. RESULTS AND DISCUSSION

3.1. Analysis of variance (ANOVA)

The analysis of variance of all fourteen traits related to yield and its component traits in maize (Table 2) clearly indicated that the mean sum of squares due to genotypes was highly significant for all the characters studied, revealing the existence of ample genetic variability among the experimental material evaluated for grain yield and its contributing traits. Further partitioning of variation showed that parents, including females and males, differed significantly for most characters, reflecting adequate diversity among parental lines. The hybrids also exhibited a highly significant mean sum of squares for all traits, demonstrating Notable variability among cross combinations. The wide

Table 2: Analysis of variance for yield and its component traits in maize

Source of variation	df	Days to 50% tasseling	Days to 50% silking	Days to maturity	Plant height	Ear height	Cob girth	Cob length
Replications	2	14.09	10.01	16.35	13.75	5.8266	1.87	2.87
Genotypes (G)	48	16.57**	16.49**	26.48**	643.69**	180.875**	4.64**	10.49**
Parents (P)	11	11.63**	11.72**	12.41	562.86**	175.386**	1.98*	6.60**
Females (F)	5	15.42**	14.46**	9.02	370.42**	117.147**	2.01	6.52**
Males (M)	5	8.36	9.52	18.09	816.32**	260.889**	2.17	7.56**
Female vs Male	1	9.00	9.00	1.00	257.76	39.0625	0.86	2.13
Hybrids (H)	35	18.83**	18.68**	31.80**	645.64**	177.945**	5.02**	10.59**
Parents vs hybrids	1	6.02	5.11	20.45	2062.12**	405.965**	24.88**	58.27**
Check vs hybrids	1	1.89	2.97	1.94	9.13	84.6842	1.39	0.68
Error	96	4.76	4.35	9.69	104.00	23.6305	1.01	1.38

Table 2: Continue...

Source of variation	df	Cob weight	No. of kernel row cob ⁻¹	No. of kernel row ⁻¹	Shelling (%)	100 kernels weight	Kernel yield plant ⁻¹	Protein content
Replications	2	31.89	0.19	7.19	3.53	4.86	14.64	0.01
Genotypes (G)	48	1894.67**	5.98**	29.47**	53.45**	41.96**	1249.04**	5.43**
Parents (P)	11	1821.89**	2.67	22.97**	16.09*	28.39**	812.20**	4.14**
Females (F)	5	1773.29**	2.49	34.85**	10.99	25.26**	635.69**	3.84**
Males (M)	5	1770.86**	3.02	11.00*	20.97*	31.16**	690.36**	3.62**
Female vs male	1	2320.03**	1.78	23.38*	17.17	30.25*	2304.00**	8.28**
Hybrids (H)	35	1747.58**	7.27**	30.45**	63.23**	37.46**	1265.52**	5.75**
Parents vs hybrids	1	9108.21**	2.37	93.59**	168.68**	378.88**	5944.01**	11.70**
Check vs hybrids	1	294.81	0.40	0.67	2.43	3.28	463.93*	1.47**
Error	96	164.60	1.63	3.81	6.97	5.07	99.18	0.10

*, ** Significant at ($p=0.05$) and ($p=0.01$) level of significance, respectively

range of diversity allowed plant breeders to select superior and desired genotypes for further crop improvement.

3.2. Genetic diversity analysis using hierarchical clustering

A total of twelve maize parents, comprising six lines and six testers, were evaluated for genetic diversity using hierarchical cluster analysis. The genotypes were grouped into four distinct clusters, indicating considerable genetic diversity among the inbreds (Figure 1). Cluster II was the largest with four genotypes, followed by Clusters III and IV with three genotypes each, while Cluster I contained only two genotypes (Table 3), reflecting variation in genetic divergence among the parents. Based on the dissimilarity matrix using Ward's method and Euclidean distance, Yadav et al. (2025) grouped 238 wheat genotypes into nine distinct clusters, indicating the presence of wide genetic diversity

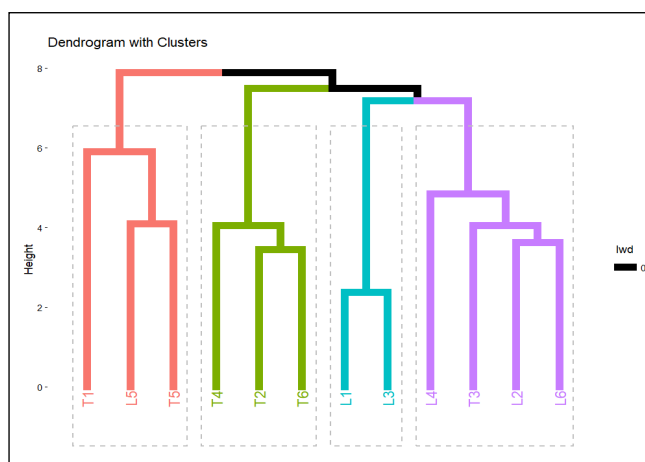


Figure 1: Hierarchical clustering of maize genotypes based on Euclidean distance using ward D2 method

Table 3: Clustering pattern of maize genotypes based on hierarchical cluster analysis

Cluster no.	Cluster member
1	IL-14-24 (L ₁), IL-17-77 (L ₃)
2	IGI-19-25 (L ₂), IL-17-01(L ₄), IL-17-81 (L ₆), IGI-19-09 (T ₃)
3	IL-17-39 (L ₅), IL-17-73 (T ₁), IL-15-23 (T ₅)
4	IL-15-19 (T ₂), IL-14-34 (T ₄), IL-17-55 (T ₆)

among the lines. The cluster plot further confirmed clear separation among clusters in multivariate space (Figure 2).

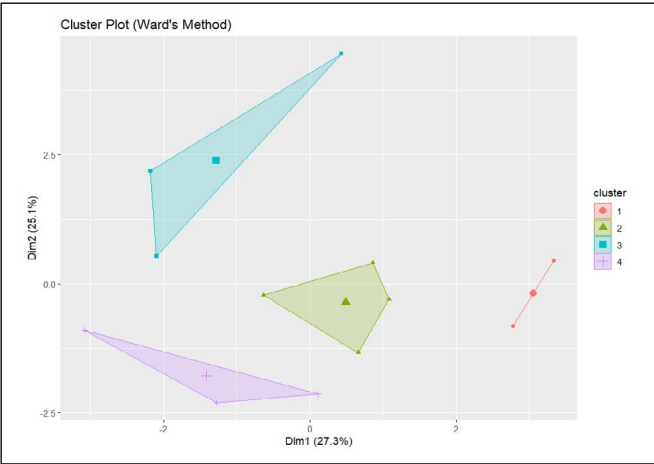


Figure 2: Cluster plot of maize genotypes based on the Ward D2 method

Genotypes grouped within the same cluster were more similar, whereas those belonging to different clusters were genetically diverse. Therefore, hybridization between genotypes from distant clusters results in higher heterosis and greater variability in segregating generations, a finding also reported by Singh and Chauhan (1980) and Mian and Bahl (1989), emphasizing that genetically distant parents tend to produce superior hybrids. The clustering pattern observed in the present study was effectively utilized to select diverse parents in breeding programmes. Crossing genotypes from divergent clusters is expected to generate maximum variability and improve selection efficiency for economically important traits. Similar results were observed by Elmyhun et al. (2026), who classified 107 maize inbred lines into three distinct clusters using hierarchical clustering based on Euclidean distance and Ward's D² method. The study revealed substantial genetic divergence among clusters, with maximum genetic distance observed between specific groups, highlighting the utility of this method in identifying genetically diverse parents for hybrid breeding.

3.3. Magnitude of heterobeltiosis and standard heterosis

The heterotic effects were estimated as percentage increase or decrease over the better parent and the standard check hybrid for all the traits studie. The magnitude of heterobeltiosis and standard heterosis, along with the number of hybrids showing significant and desirable heterotic effects for the fourteen characters, are summarized in Tables 4, 5 and 6. Traits such as days to 50% tasseling,

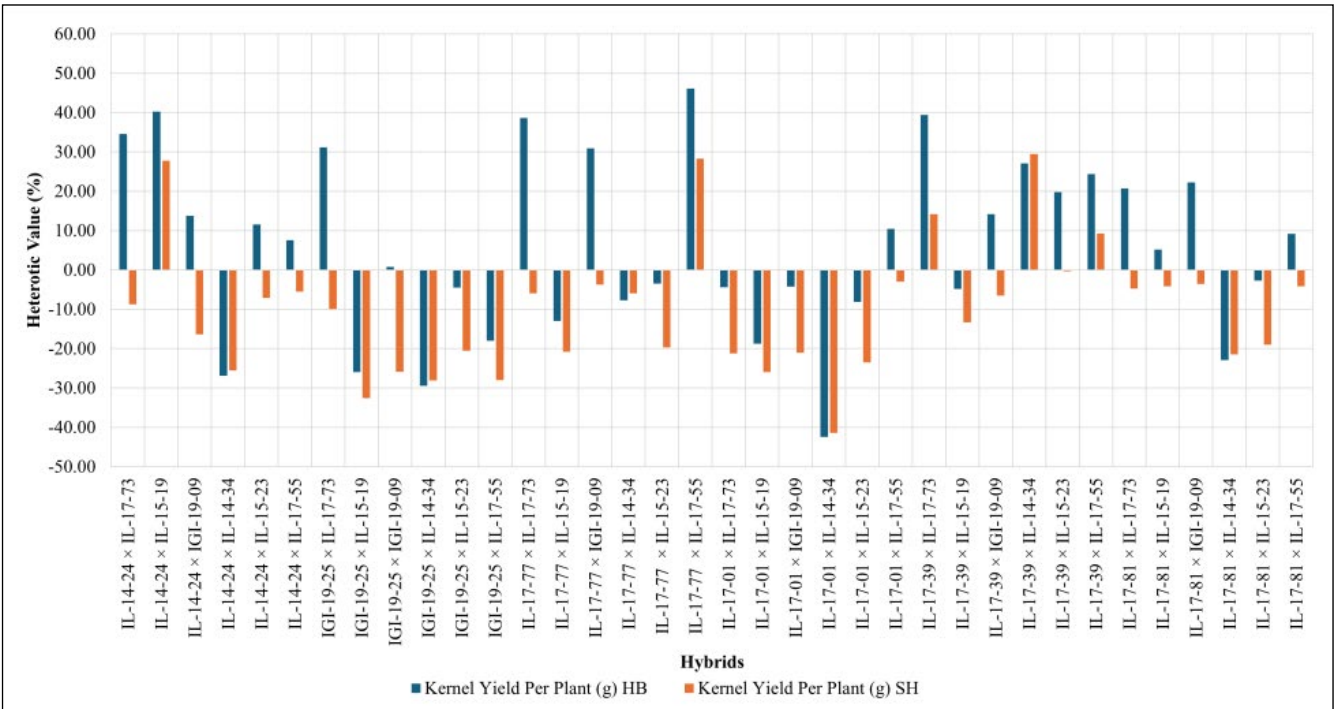


Figure 3: Heterobeltiosis (HB) and standard heterosis (SH) value of hybrids for kernel yield plant⁻¹

Sl. No.	Hybrids	Days to 50% tasseling		Days to 50% silking		Days to maturity		Plant height		Ear height		Cob girth	
		HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)
1.	IL-14-24×IL-17-73	2.47	1.84	1.15	1.73	-0.33	-0.33	22.97**	6.61	21.18**	-1.79	-7.15	-7.66
2.	IL-14-24×IL-15-19	6.79*	6.13	6.32*	6.94*	5.30*	3.92	36.12**	4.03	35.6**	-4.28	-7.15	-7.66
3.	IL-14-24×IGI-19-09	7.41*	6.75*	6.32*	6.94*	-0.66	-2.29	16.91*	1.36	19.37**	-3.26	16.82*	19.94**
4.	IL-14-24×IL-14-34	-2.47	-3.07	-4.02	-3.47	-5.56*	-5.56*	13.94*	-1.22	6.59	-13.62**	23.24**	12.04
5.	IL-14-24×IL-15-23	1.85	1.23	1.15	1.73	-0.98	-0.98	27.39**	10.44	28.43**	4.09	-7.18	0.50
6.	IL-14-24×IL-17-55	-3.09	-3.68	-3.45	-2.89	-1.69	-4.90*	16.84*	1.29	23.82**	0.35	5.06	7.58
7.	IGI-19-25×IL-17-73	4.29	4.29	4.62	4.62	0.65	0.65	7.84	6.04	5.84	-3.62	2.43	-7.16
8.	IGI-19-25×IL-15-19	13.5**	13.5**	12.72**	12.72**	4.97*	3.59	30.07**	-0.60	35.85**	-4.10	-10.84	-4.13
9.	IGI-19-25×IGI-19-09	0.61	0.61	-0.58	-0.58	2.33	0.65	8.82	7.00	8.40	0.14	-20.6**	-14.63*
10.	IGI-19-25×IL-14-34	4.91	4.91	4.62	4.62	0.33	0.33	21.21**	11.72*	9.13	-5.37	-3.72	3.53
11.	IGI-19-25×IL-15-23	5.52	5.52	5.20	5.20	1.31	1.31	-3.79	-5.40	1.62	-6.13	-3.23	4.77
12.	IGI-19-25×IL-17-55	1.23	0.61	1.16	1.16	6.08*	2.61	13.93*	1.37	22.74**	1.88	1.92	9.59
13.	IL-17-77×IL-17-73	13.13**	11.04**	11.11**	9.83**	2.61	2.94	26.83**	-1.04	25.42**	-9.28	-4.51	2.67
14.	IL-17-77×IL-15-19	3.75	1.84	4.09	2.89	1.66	0.33	47.76**	12.93*	49.88**	5.80	4.57	3.99
15.	IL-17-77×IGI-19-09	6.87*	4.91	7.02*	5.78	0.66	-0.98	48.54**	15.89**	48.75**	7.59	-7.97	-5.51
16.	IL-17-77×IL-14-34	-0.63	-2.45	0.00	-1.16	-5.21*	-4.90*	7.58	-16.06**	6.43	-23.02**	22.24**	11.13
17.	IL-17-77×IL-15-23	1.25	-0.61	0.00	-1.16	-6.19*	-5.88*	25.72**	-1.91	30.73**	-5.44	-2.80	5.23
18.	IL-17-77×IL-17-55	5.63	3.68	4.68	3.47	4.05	0.65	31.29**	2.43	40.04**	1.29	0.65	3.06
19.	IL-17-01×IL-17-73	-0.60	2.45	1.14	2.31	2.00	0.00	-15.39**	-17.97**	-14.53*	-22.16**	37.08**	24.24**
20.	IL-17-01×IL-15-19	1.20	3.07	1.14	2.31	3.67	1.63	19.13*	-8.95	21.02**	-14.58**	-1.50	1.13
21.	IL-17-01×IGI-19-09	-5.95	-3.07	-4.00	-2.89	-3.33	-5.23*	-14.81*	-17.4**	-15.11**	-22.69**	-10.63	-10.14

Table 4: Continue...

Sl. No.	Hybrids	Days to 50% tasseling		Days to 50% silking		Days to maturity		Plant height		Ear height		Cob girth	
		HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)
22.	IL-17-01×IL-14-34	-0.60	1.84	1.14	2.31	0.33	-1.63	-0.34	-8.14	-13.76*	-25.22**	-12.65*	-5.43
23.	IL-17-01×IL-15-23	-2.38	0.61	0.00	1.16	2.33	0.33	-6.47	-9.31	-4.96	-13.45**	2.61	5.07
24.	IL-17-01×IL-17-55	2.47	1.84	1.72	2.31	4.05	0.65	27.69**	13.61*	28.65**	6.78	15.04*	15.67*
25.	IL-17-39×IL-17-73	-5.08	3.07	-4.76	4.05	0.00	2.94	-16.5**	-23.8**	-19.15**	-27.43**	24.63**	23.94**
26.	IL-17-39×IL-15-19	-2.41	-0.61	-2.29	-1.16	1.32	0.00	18.9*	-9.13	20.31**	-15.07**	6.82	9.67
27.	IL-17-39×IGI-19-09	-8.33**	-5.52	-7.82**	-4.62	-3.99	-5.56*	-0.60	-9.29	-6.35	-15.94**	23.67**	19.48**
28.	IL-17-39×IL-14-34	-4.19	-1.84	-3.93	-1.16	-3.91	-3.59	14.00*	4.03	-2.78	-15.7**	17.81**	27.55**
29.	IL-17-39×IL-15-23	-1.18	3.07	1.12	4.05	-1.28	0.98	8.68	-0.82	5.74	-5.09	18.03**	20.85**
30.	IL-17-39×IL-17-55	-9.26**	-9.82**	-9.77**	-9.25**	-6.76**	-9.80**	7.58	-4.28	17.77**	-2.24	14.66*	10.77
31.	IL-17-81×IL-17-73	1.24	0.00	0.58	0.58	-2.30	-2.61	18.25**	11.86*	9.7	-0.10	9.94	9.34
32.	IL-17-81×IL-15-19	6.83*	5.52	5.20	5.20	4.97*	3.59	27.9**	-2.25	37.27**	-3.10	15.83*	18.93**
33.	IL-17-81×IGI-19-09	2.48	1.23	1.73	1.73	3.32	1.63	8.01	2.18	9.61	1.49	9.21	3.20
34.	IL-17-81×IL-14-34	-6.83*	-7.98*	-6.36*	-6.36*	-1.31	-1.63	-15.59*	-22.2**	-13.77*	-25.23**	-10.99	-3.64
35.	IL-17-81×IL-15-23	0.62	-0.61	0.58	0.58	-1.64	-1.96	7.28	1.49	8.85	0.79	-0.91	1.46
36.	IL-17-81×IL-17-55	4.35	3.07	3.47	3.47	3.72	0.33	14.55*	1.92	25.57**	4.23	0.99	-4.57
S.E.(Sij) ±		1.78		1.70		2.54		8.33		3.97		0.82	
Range													
Min.		-9.26	-9.82	-9.77	-9.25	-6.76	-9.80	-16.50	-23.80	-19.15	-27.43	-20.60	-14.63
Max.		13.50	13.50	12.72	12.72	6.08	3.92	48.54	15.89	49.88	7.59	37.08	27.55
No. of total significant crosses		9	5	8	6	8	7	25	10	23	12	13	9
Positive		6	3	5	4	4	0	21	5	18	0	11	8
Negative		3	2	3	2	4	7	4	5	5	12	2	1

*, ** Significant at ($p=0.05$) and ($p=0.01$) level of significance

Sl. No.	Hybrids	Cob length		Cob weight		No. of kernel row cob ⁻¹		No. of kernel row ⁻¹		Shelling (%)		100 Kernels weight	
		HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)
1.	IL-14-24×IL-17-73	7.61	-7.61	34.55**	-12.94*	10.53	0.00	21.86**	4.49	8.32**	4.99	28.61**	-6.47
2.	IL-14-24×IL-15-19	21.14**	19.08**	22.79**	21.76**	9.52	9.52	13.49**	17.28**	8.32**	4.99	38.28**	16.28**
3.	IL-14-24×IGI-19-09	24.78**	7.12	19.49*	-8.38	-4.76	-4.76	10.4	-0.43	14.54**	11.02**	5.28	-15.06*
4.	IL-14-24×IL-14-34	2.75	-0.67	-24.84**	-19.31**	5.26	-4.76	5.81	4.63	-4.39	-5.85*	-22.09**	-23.86**
5.	IL-14-24×IL-15-23	7.45	4.93	25.08**	7.21	0.00	-4.76	15.65**	7.94	0.03	-2.51	-10.47	-9.45
6.	IL-14-24×IL-17-55	9.80	-1.31	-0.19	-10.89	20.00*	14.29	9.49	7.06	-8.84**	-10.01**	-6.13	-20**
7.	IGI-19-25×IL-17-73	-10.06	-22.5**	32.2**	-5.57	-9.09	-4.76	18.5**	1.61	6.96*	5.45	23.84**	-5.72
8.	IGI-19-25×IL-15-19	-10.73	-12.25*	-27.14**	-27.75**	-13.64	-9.52	-21.3**	-18.68**	2.52	-2.10	10.57	-7.02
9.	IGI-19-25×IGI-19-09	8.83	-6.22	9.66	-15.91*	-18.18*	-14.29	12.62*	1.57	2.02	-2.58	-4.97	-23.33**
10.	IGI-19-25×IL-14-34	-1.32	-4.60	-26.59**	-21.19**	-13.64	-9.52	-8.21	-9.23	-7.65**	-9.06**	-14.52*	-16.47**
11.	IGI-19-25×IL-15-23	1.52	-0.86	3.86	-10.98	-22.73**	-19.05*	8.81	1.56	0.98	-1.58	-9.83	-8.81
12.	IGI-19-25×IL-17-55	3.33	-7.12	-12.24	-21.64**	-18.18*	-14.29	-19.76**	-21.54**	-4.11	-5.35	17.92*	0.50
13.	IL-17-77×IL-17-73	8.93	-2.15	42.85**	-4.57	20.00*	14.29	22.12**	4.71	-7.27*	-8.58**	2.36	-15.09*
14.	IL-17-77×IL-15-19	-20.72**	-22.07**	-22.11**	-22.76**	-4.76	-4.76	-22.27**	-19.68**	18.52**	12.84**	18.11*	-0.68
15.	IL-17-77×IGI-19-09	8.87	-2.21	32.77**	1.81	9.52	9.52	9.83	-0.94	11.86**	6.76*	17.75*	-2.32
16.	IL-17-77×IL-14-34	2.37	-1.04	-8.57	-1.84	15.00	9.52	5.87	4.69	-2.91	-4.4	-10.62	-12.65*
17.	IL-17-77×IL-15-23	-3.57	-5.83	3.12	-11.62	20.00*	14.29	-2.40	-8.91	4.85	2.19	-17.31**	-16.38**
18.	IL-17-77×IL-17-55	35.45**	21.74**	33.2**	18.93**	20.00*	14.29	15.36**	12.80*	-5.04	-6.26*	38.24**	17.82**
19.	IL-17-01×IL-17-73	-1.66	-20.96**	-13.38	-17.57**	5.00	0.00	14.52*	2.64	12.2**	10.61**	-20.06**	-21.88**
20.	IL-17-01×IL-15-19	-11.59*	-13.09*	-22.14**	-22.79**	-9.52	-9.52	-18.46**	-15.74**	5.90*	1.08	4.94	2.56
21.	IL-17-01×IGI-19-09	8.05	-14.64**	-11.51	-15.78*	-19.05*	-19.05*	16.43**	5.01	-0.69	-2.22	0.35	-1.93

Table 5: Continue...

Sl. No.	Hybrids	Days to 50% tasseling		Days to 50% silking		Days to maturity		Plant height		Ear height		Cob girth	
		HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)
22.	IL-17-01×IL-14-34	-2.31	-5.56	-47.41**	-43.55**	-15.00	-19.05*	-11.94*	-12.92*	2.11	-0.49	-22.91**	-24.66**
23.	IL-17-01×IL-15-23	-0.54	-2.88	-15.09*	-19.19**	-15.00	-19.05*	8.95	1.69	0.38	-0.91	-7.88	-6.83
24.	IL-17-01×IL-17-55	16.55**	4.76	-1.17	-5.94	15.00	9.52	-1.64	-3.82	6.47*	4.97	5.26	2.86
25.	IL-17-39×IL-17-73	1.66	4.25	35.65**	20.26**	21.05*	9.52	4.42	3.64	2.17	-2.80	25.77**	4.33
26.	IL-17-39×IL-15-19	-4.18	-1.74	-10.84	-11.59	-19.05*	-19.05*	-11.11*	-8.14	5.32	0.53	18.68*	-0.20
27.	IL-17-39×IGI-19-09	-0.63	1.90	10.98	-1.61	-9.52	-9.52	6.95	6.16	-2.39	-3.89	19.34*	-1.00
28.	IL-17-39×IL-14-34	18.8**	21.82**	15.70*	24.21**	26.32**	14.29	14.99**	14.13**	12.32**	9.47**	17.94**	15.26*
29.	IL-17-39×IL-15-23	17.44**	20.43**	20.07**	6.45	-5.00	-9.52	11.34*	10.51*	-4.76	-5.99*	7.25	8.47
30.	IL-17-39×IL-17-55	-3.59	-1.14	20.02**	7.16	0.00	-4.76	12.65*	11.81*	-0.81	-2.21	32.11**	12.59
31.	IL-17-81×IL-17-73	17.82*	-5.30	24.82**	6.72	0.00	4.76	-4.91	1.43	-5.25	-9.96**	45.00**	3.81
32.	IL-17-81×IL-15-19	-5.49	-7.10	13.81*	12.85	-9.09	-4.76	-11.96*	-6.09	-0.95	-5.46	34.84**	13.39*
33.	IL-17-81×IGI-19-09	14.34*	-9.32	20.43**	2.98	0.00	4.76	-17.57**	-12.08*	-0.50	-2.03	37.7**	11.10
34.	IL-17-81×IL-14-34	-7.41	-10.49	-21.56**	-15.8*	-9.09	-4.76	-19.74**	-14.39**	0.82	-1.74	-0.90	-3.15
35.	IL-17-81×IL-15-23	-5.17	-7.40	5.88	-9.24	-18.18*	-14.29	-27.74**	-22.92**	-8.05**	-9.24**	4.87	6.06
36.	IL-17-81×IL-17-55	-1.92	-11.84*	12.05	0.05	-4.55	0.00	-13.3**	-7.52	-4.27	-5.62*	14.85*	-2.11
S.E.(Sij) ±		0.96		10.48		1.04		1.59		2.16		1.84	
Range													
Min.		-20.72	-22.50	-47.41	-43.55	-22.73	-19.05	-27.74	-22.92	-8.84	-10.01	-22.91	-24.66
Max.		35.45	21.82	42.85	24.21	26.32	14.29	22.12	17.28	18.52	12.84	45.00	17.82
No. of total significant crosses		10	11	23	17	12	5	23	13	14	14	21	15
Positive		8	4	15	4	6	0	12	5	10	5	16	5
Negative		2	7	8	13	6	5	11	8	4	9	5	10

*, ** Significant at ($p=0.05$) and ($p=0.01$) level of significance

days to 50% silking, days to maturity, plant height and ear height with lower mean values were considered desirable; hence, the parent with the lower value was treated as the better parent for heterosis estimation. In contrast, positive heterotic effects were considered advantageous for all other yield and yield-contributing characters.

Kernel yield plant⁻¹ (Table 6), a key economic trait for hybrid development, exhibited significant heterobeltiosis in twelve out of thirty-six hybrids, ranging from -42.45% (IL-17-01×IL-14-34) to 46.09% (IL-17-77×IL-17-55). The cross IL-17-77×IL-17-55 recorded the highest heterobeltiosis, followed by IL-14-24×IL-15-19 (40.31%) and IL-17-39×IL-17-73 (39.44%). Standard heterosis over the check hybrid GAYMH-3 ranged from -41.36% to 29.48%, with twenty-one hybrids showing significant effects, among which four exhibited desirable positive heterosis; the best crosses were IL-17-39×IL-14-34 (29.48%), IL-17-77×IL-17-55 (28.32%) and IL-14-24×IL-15-19 (27.79%). The magnitude of both heterobeltiosis and standard heterosis varied widely in positive and negative directions (Figure 3) which indicated indicating significant variability among hybrids, Ravat et al. (2025) similarly reported significant positive heterobeltiosis and standard heterosis for kernel yield per plant and its component traits, indicating a potential for hybrid development. These findings were supported by earlier reports by Gurjar et al. (2022), Patel et al. (2022), Reddy and Delvadiya (2023), Tabu et al. (2023) and Tejaswini et al. (2023).

For earliness traits, hybrid IL-17-39×IL-17-55 exhibited the highest significant negative heterobeltiosis and standard heterosis for days to 50% tasseling, silking and maturity, followed by IL-17-81×IL-14-34 for days to tasseling and IL-17-77×IL-15-23 for days to maturity indicating their suitability for developing early maturing hybrids (Table 4). The expression of negative heterosis for flowering and maturity traits is desirable in maize as it facilitates early harvesting and crop adaptation under diverse environments. Similar findings were reported by Patel et al. (2022), who observed significant negative heterosis for tasseling and silking in hybrids such as WNC 40324×BLD 98 and BLD 109×IMR 113. Likewise, Reddy and Delvadiya (2023) also documented significant negative heterosis for earliness traits in crosses including L7×T3, L5×T5 and L8×T7, thereby supporting the present findings. For plant architecture, hybrid IL-17-39×IL-17-73 exhibited significantly desirable heterobeltiosis and standard heterosis for reduced plant and ear height, followed by IL-17-81×IL-14-34 for plant height and IL-17-01×IL-14-34 for ear height indicating suitability for lodging resistance and easy harvesting. Comparable results were documented by Teja et al. (2024), wherein the hybrids CML138×CML193 and CML332×CML145 exhibited significant negative SCA effects and standard

Table 6: Magnitude of heterobeltiosis (HB) and standard heterosis (SH) for yield and its components traits in maize

Sl. No.	Hybrids	Kernel yield plant ⁻¹		Protein content	
		HB (%)	SH (%)	HB (%)	SH (%)
1.	IL-14-24×IL-17-73	34.59**	-8.7	31.98	-17.36**
2.	IL-14-24×IL-15-19	34.59**	-8.70	1.98	-17.36**
3.	IL-14-24×IGI-19-09	40.31**	27.79**	33.84**	8.46**
4.	IL-14-24×IL-14-34	13.82	-16.32*	10.18**	-10.71**
5.	IL-14-24×IL-15-23	-26.86**	-25.48**	-19.30**	-34.61**
6.	IL-14-24×IL-17-55	11.59	-7.11	-12.88**	-10.84**
7.	IGI-19-25×IL-17-73	7.57	-5.51	32.07**	7.02*
8.	IGI-19-25×IL-15-19	31.19**	-9.94	-23.24**	-29.11**
9.	IGI-19-25×IGI-19-09	-25.96**	-32.56**	-27.20**	-32.76**
10.	IGI-19-25×IL-14-34	0.80	-25.90**	-24.36**	-30.13**
11.	IGI-19-25×IL-15-23	-29.40**	-28.06**	-11.78**	-18.51**
12.	IGI-19-25×IL-17-55	-4.50	-20.50**	-3.33	-1.07
13.	IL-17-77×IL-17-73	-18.00*	-27.97**	-0.76	-8.33**
14.	IL-17-77×IL-15-19	38.69**	-5.91	1.24	-29.72**
15.	IL-17-77×IGI-19-09	-12.99	-20.75**	23.9**	-13.18**
16.	IL-17-77×IL-14-34	30.96**	-3.73	16.50**	-11.33**
17.	IL-17-77 ×IL-15-23	-7.69	-5.95	4.09	-27.96**
18.	IL-17-77 ×IL-17-55	-3.47	-19.65**	-23.83**	-22.04**
19.	IL-17-01×IL-17-73	46.09**	28.32**	30.49**	5.58
20.	IL-17-01×IL-15-19	-4.35	-21.15**	-10.65**	-3.61
21.	IL-17-01×IGI-19-09	-18.74**	-25.98**	1.56	9.56**

Table 6: Continue...

Sl. No.	Hybrids	Kernel yield plant ⁻¹		Protein content	
		HB (%)	SH (%)	HB (%)	SH (%)
22.	IL-17-01×IL-14-34	-42.45**	-41.36**	-20.81**	-14.57**
23.	IL-17-01×IL-15-23	-8.09	-23.49**	14.73**	23.77**
24.	IL-17-01×IL-17-55	10.48	-2.95	17.77**	27.05**
25.	IL-17-39×IL-17-73	39.44**	14.19*	-11.31**	-25.62**
26.	IL-17-39×IL-15-19	-4.85	-13.34*	27.51**	6.94*
27.	IL-17-39×IGI-19-09	14.18	-6.50	4.06	-12.73**
28.	IL-17-39×IL-14-34	27.07**	29.48**	42.29**	19.33**
29.	IL-17-39×IL-15-23	19.80*	-0.28	17.25**	19.99**
30.	IL-17-39×IL-17-55	24.38**	9.26	31.38**	10.18**
31.	IL-17-81×IL-17-73	20.72*	-4.73	-15.15**	-15.15**
32.	IL-17-81×IL-15-19	5.23	-4.15	-24.18**	-24.18**
33.	IL-17-81×IGI-19-09	22.25**	-3.52	-12.07**	-12.07**
34.	IL-17-81×IL-14-34	-22.87**	-21.41**	-23.40**	-23.40**
35.	IL-17-81×IL-15-23	-2.65	-18.96**	3.21	5.62
36.	IL-17-81×IL-17-55	9.19	-4.09	-11.49**	-11.49**
S.E.(Sij) ±		8.13		0.25	
Range					
Min.		-42.45	-41.36	-27.20	-34.61
Max.		46.09	29.48	42.29	27.05
No. of total significant crosses		19	21	28	32
Positive		12	4	12	9
Negative		7	17	16	23

*, ** Significant at ($p=0.05$) and ($p=0.01$) level of significance, respectively

heterosis for plant height, indicating their suitability for developing compact and lodging tolerant maize hybrids under stress conditions. The present findings are further supported by the earlier reports of Patel et al. (2022), Reddy and Delvadiya (2023). Among the cob related traits (Table 5), the hybrid IL-17-39×IL-14-34 exhibited superior performance, recording the highest desirable standard heterosis for cob girth, cob length and cob weight, followed by IL-17-77×IL-17-55. Similar findings were reported by Tejaswini et al. (2023), wherein hybrids such as PFSR-127×BML-10, PFSR-151×MGC-49 and MGC-49×ML-14 expressed significant positive heterobeltiosis and standard heterosis for ear length and ear girth. In particular, the hybrid BML-10×ML-14 recorded the highest positive standard heterosis for ear girth, while PFSR-127×BML-10 exhibited superior performance for ear length, thereby confirming the importance of cob associated traits in enhancing yield potential in maize hybrids. The present findings are also in close conformity with the reports of Gami et al. (2018) and Sandesh et al. (2018), who similarly observed significant positive heterotic effects for cob traits in maize. For kernel traits, IL-14-24×IL-15-19 exhibited the highest positive standard heterosis for kernels per row, followed by IL-17-39×IL-14-34, which indicated their potential for improving yield components. Similar findings were reported by Tesfaye and Sime (2021), who observed significant positive heterobeltiosis for number of kernels per row, with values ranging from 13.6% to 57.4%, demonstrating the importance of this trait in heterosis breeding. These findings were in agreement with earlier reports by Gurjar et al. (2022), Reddy and Delvadiya (2023) and Tejaswini et al. (2023). The hybrid IL-17-77×IL-17-73 recorded the highest desirable heterobeltiosis and standard heterosis, suggesting its superiority in grain recovery. Similar observations were reported by Sandesh et al. (2018), who observed significant positive standard heterosis for shelling percentage in several maize hybrids, with heterotic effects ranging from moderate to high magnitude over standard checks, thereby emphasizing the importance of heterosis breeding for improving grain recovery efficiency in maize. The present findings are also in close conformity with the reports of Dodhatti et al. (2022) and Patel et al. (2022), who similarly documented desirable heterotic responses for shelling percentage and related yield contributing traits in maize hybrids.

For 100-kernel weight (Table 5), the hybrids IL-17-77×IL-17-55 and IL-14-24×IL-15-19 recorded the highest positive standard heterosis, marking their potential for enhancing grain mass and overall productivity. In agreement

with these results, Bhatla et al. (2025) reported significant positive standard heterosis for test weight in multiple hybrid combinations, confirming the importance of this trait in heterosis-based maize improvement. Similar results were also documented by, Dodhatti et al. (2022), Reddy and Delvadiya (2023) and Tabu et al. (2023).

In addition to yield-related traits, certain hybrids also demonstrated significant heterosis for nutritional quality, particularly protein content. The hybrid IL-17-39×IL-14-34 exhibited the highest desirable heterobeltiosis (42.29%), followed by IL-14-24×IL-15-19 (33.84%) and IL-14-24×IL-17-55 (32.07%) (Table 6), indicating significant improvement over their respective better parents. The present findings are in close agreement with the reports of Gurjar et al. (2020) and Abdel-Moneam et al. (2020), who also documented significant positive heterotic effects for quality and yield contributing traits in maize hybrids.

3.4. Relationship between parental diversity and heterobeltiosis

Overall, the results indicated that crosses involving elite parental lines such as IL-17-39, IL-17-77 and IL-14-24 with testers like IL-14-34, IL-17-55 and IL-15-19 exhibited superior heterosis for yield contributing traits. The cluster analysis revealed that these parents belonged to different clusters, with IL-14-24 (Cluster I), IL-17-77 (Cluster I), IL-17-39 (Cluster III) and testers IL-14-34, IL-17-55 and IL-15-19 grouped in Cluster IV (Table 1), indicating genetic divergence among them. The involvement of parents from distinct clusters suggested that the observed high heterosis may be attributed to their wide genetic diversity, as genotypes from divergent clusters were more likely to produce superior hybrids due to greater genetic complementation. Hence, the present findings confirmed that genetically diverse parents identified through cluster analysis were effectively utilized to exploit heterosis and improve yield performance in maize.

4. CONCLUSION

The study aimed to identify superior maize hybrids with high heterosis for yield and its contributing traits. The crosses IL-17-39×IL-14-34, IL-17-77×IL-17-55 and IL-14-24×IL-15-19 exhibited significant standard heterosis and heterobeltiosis for kernel yield plant⁻¹ and related traits, which indicated their potential for hybrid development. The presence of considerable genetic diversity among parental lines further supported the effectiveness of selection and hybridization. Therefore, these hybrids were recommended for effective use in breeding programmes to enhance maize productivity.

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