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Combining ability analysis and estimation of heterosis for grain yield and its component traits in maize (*Zea mays* L.)

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Abstract
The analysis of variance revealed highly significant differences among the genotypes for all studied traits, indicating that the experimental materials exhibited sufficient genetic variability for all characteristics assessed. The estimates of heterosis over the better parent ranged from-9.66% to 62.42% concerning grain yield per plant. The cross CM 212-2 × GYL 1 (62.42%) showed the greatest positive heterosis compared to the better parent, followed by GYL 1 × GYL 10 (46.65%) and CM 111 × GYL 1 (36.95%). Economic heterosis varied between-43.63% and 38.30%. The combination GYL 4 × GYL 10 (38.30%) demonstrated the highest significant positive heterosis over the standard check, trailed by CM 212-2 × GYL 4 (36.59%) and GYL 4 × GYL 5 (33.66%). Further investigation of these crosses may result in the creation of desirable maize hybrids.

Keywords: Maize, heterosis, half-diallel mating design

Introduction
Maize (*Zea mays* L., 2n = 2x = 20) is one of the most adaptable crops, thriving in a variety of agro-climatic environments. It belongs to the grass family Poaceae, within the tribe Maydeae, and is amongst the earliest cultivated crops (Sleper and Poehlman, 2006). Known globally as the "Queen of cereals," maize possesses the highest genetic yield potential of all cereals. The Meso-American region (Mexico and Central America) is recognized as maize's origin. As a C_4 plant, it demonstrates greater physiological efficiency and resilience to changing climate conditions, exhibiting extensive genetic diversity and the ability to flourish in diverse environmental settings, including tropical, subtropical, and temperate agro-climatic zones. Approximately 1225.10 million tonnes of maize is produced collectively by more than 170 countries across an area of 153.51 million hectares, achieving an average productivity of 7.98 tonnes per hectare (Anonymous, 2024). It has established itself as a significant industrial crop worldwide, with 83% of global production utilized in feed, starch, and biofuel sectors. In India, maize is grown over 11.24 million hectares, yielding 37.66 million tonnes of grain with an average productivity of 3350.60 kilograms per hectare (Anonymous, 2025). Yield is a trait governed by multiple genes and influenced by various factors. The ongoing adoption and enhancement of varieties have allowed maize productivity to reach unprecedented heights. For plant breeders, identifying appropriate parent lines with superior genetic potential is essential for developing improved varieties. The concept of heterosis guides breeding programs by facilitating the selection of exceptional hybrids. The overall heterosis is utilized as a benchmark in selecting suitable lines and crossing combinations, serving as a cornerstone for genetic diversity. High-yielding single-cross hybrids with significant heterotic effects can be developed to tackle productivity challenges in maize. Understanding the nature and extent of heterosis aids in pinpointing superior cross combinations that may yield desirable segregants in future generations.
Considering all the factors mentioned above, this study was designed to assess heterobeltiosis and standard heterosis for grain yield and its associated traits, as well as to identify the best crosses along with their parent varieties.

Materials and Methods

The experimental material consisted of eight genotypes, CM 111, CM 212-2, GYL 1, GYL 4, GYL 5, GYL 10, GYL 11, and H-07-R-01-3, along with their 28 hybrids developed through a half-diallel mating design and one standard check (GAYMH 3). The experimental setup comprised 37 entries, which included 8 parental lines, 28 hybrids, and 1 standard check, and was evaluated in a randomized block design with three replications during the *kharif* season of 2024 at the Instructional Farm of the Department of Agronomy at Junagadh Agricultural University, Junagadh. The crossing program was conducted in the summer of 2024. The spacing between rows and plants was maintained at 60 cm and 20 cm, respectively. All recommended agricultural practices and pest management strategies were implemented to cultivate a healthy crop. Five representative plants from each genotype were randomly chosen in each replication to record observations on 13 traits, including plant height, cob height, cob length, cob girth, cob weight, number of rows per cob, number of grains per row, shelling percentage, 100-grain weight, and grain yield per plant, with days to 50 percent tasseling, days to 50 percent silking, and days to maturity noted at the plot level.

Results and Discussion

A variance analysis indicated that there were significant differences among the genotypes for all traits examined, suggesting that the experimental materials exhibited ample genetic diversity for all these characteristics. The variance attributed to the genotypes was further divided into variance from the parents, hybrids, and the differences between parents and hybrids. Significant differences among the parents were observed for all traits studied, except for the number of rows per cob. The mean squares attributed to the comparison between parents and hybrids were also significant for traits such as days to 50 percent tasseling, days to 50 percent silking, days to maturity, plant height, cob height, cob length, cob girth, cob weight, number of rows per cob, number of grains per row, shelling percentage, 100-grain weight, and grain yield per plant, indicating that the hybrids' performance as a collective group differed from that of the parents for these traits.

For earliness, it is preferable to have negative heterotic effects regarding the number of days to 50 percent tasseling occurs. The range of heterobeltiosis (Table 2) varied from -21.18% (GYL 10 × H-07-R-01-3) to 1.04% (GYL 4 × GYL 10). The hybrids GYL 10 × H-07-R-01-3 (-21.18%), GYL 10 × GYL 11 (-19.51%), GYL 5 × H-07-R-01-3 (-19.70%), and GYL 1 × H-07-R-01-3 (-18.72%) demonstrated significant and negative heterobeltiosis (Table 2). The standard heterosis (Table 2) ranged from-8.98% (GYL 1 × GYL 4) to 16.77% (GYL 4 × GYL 10) when compared to the check hybrid GAYMH 3. Among the 28 hybrids, only two, GYL 1 × GYL 4 (-8.98%) and GYL 10 × H-07-R-01-3 (-4.19%), showed significant and negative standard heterosis. From the 28 hybrids evaluated, two hybrids displayed significant and desirable (negative) heterosis in comparison to the standard check variety GAYMH 3 (Table 2). These findings align with the research conducted by Saidaiah *et al.* (2008) [27], Shete *et al.* (2011) [29], Sundararajan and Kumar (2011) [30], Avinashe *et al.* (2013) [9], Bekele and Rao (2013) [11], and Kumar *et al.* (2019) [18].

Table 1: Analysis of variance (Mean squares) for experimental design for grain yield and its component traits in maize

Source of variation	d.f.	Days to 50 percent tasseling	Days to 50 percent silking	Days to maturity	Plant height (cm)	Cob height (cm)	Cob length (cm)
Replications	2	0.48	0.69	1.58	3598.82**	1757.88**	3.06
Genotypes	35	60.03**	50.54**	36.61**	3202.48**	819.37**	13.44**
Parents (P)	7	49.23**	48.95**	54.74**	2259.75**	635.34**	3.56**
Hybrids (H)	27	43.27**	43.83**	28.95**	3146.31**	842.83**	13.04**
P *vs.* H	1	588.13**	242.88**	116.67**	11318.20**	1474.24**	93.40**
Error	70	0.78	0.87	1.26	44.38	14.72	1.43

Source of variation	d.f.	Cob girth (cm)	Cob weight (g)	Number of rows per cob	Number of grains per row	Shelling percentage (%)	100-grain weight (g)	Grain yield per plant (g)
Replications	2	0.38	35.02	0.69	1.51	11.34	0.07	15.38
Genotypes	35	4.22**	1451.77**	4.95**	34.12**	178.81**	22.54**	2026.58**
Parents (P)	7	3.78**	1522.93**	2.19	48.16**	101.55**	23.19**	1548.10**
Hybrids (H)	27	3.35**	1395.50**	5.08**	30.88**	202.34**	22.23**	1884.42**
P *vs.* H	1	31.00**	2472.86**	20.77**	23.43**	84.51**	26.45**	9214.08**
Error	70	0.52	52.68	1.14	2.80	5.82	1.98	91.09

*, ** Significant at 5% and 1% levels, respectively, P *vs.* H = Parents *vs.* Hybrids

For achieving earlier silking, it is beneficial to have heterotic effects that are negative regarding the number of days to 50 percent silking. The heterobeltiosis (Table 2) ranged from-18.75% (GYL 10 × H-07-R-01-3) to 2.51% (GYL 4 × GYL 10). The hybrids such as GYL 10 × H-07-R-01-3 (-18.75%), GYL 5 × GYL 11 (-18.48%), GYL 11 × H-07-R-01-3 (-15.64%), and CM212-2 × GYL 10 (-15.31%) showed significant negative heterobeltiosis. The standard heterosis (Table 2) varied from-11.35% (GYL 1 × GYL 4) to 12.43% (CM 111 × CM 212-2) compared to the check hybrid GAYMH 3. Out of 28 hybrids, eight displayed significant negative standard heterosis. The top three early hybrids, namely GYL 1 × GYL 4 (-11.35%), GYL 10 × H-07-R-01-3 (-8.65%), and GYL 5 × GYL 11 and CM 111 × GYL 5 (-7.03%) exhibited significant and favorable standard heterosis over GAYMH 3. These findings align with the results reported by Shete *et al.* (2011) [29], Sundararajan and Kumar (2011) [30], Avinashe *et al.* (2013) [9], Bekele and Rao (2013) [11], Karim *et al.* (2018) [17], and Tejaswini *et al.* (2023) [32].

For achieving earliness, it is beneficial to have heterotic effects that are negative in relation to the days to maturity. The range of heterobeltiosis (Table 2) was between-6.48% (GYL 5 × H-07-R-01-3) and 8.93% (CM 111 × GYL 10). The hybrids GYL 5 × H-07-R-01-3 (-6.48%) ranked first, followed by GYL 1 × GYL 5 (-5.28%), GYL 10 × GYL 11

(-4.11%), and GYL 11 × H-07-R-01-3 (-3.75%), all of which demonstrated noteworthy negative heterobeltiosis. The standard heterosis (Table 2) varied from-4.27% (GYL 1 × GYL 5) to 8.90% (GYL 4 × H-07-R-01-3) compared to the check hybrid GAYMH 3. Out of 28 hybrids, three exhibited significant negative standard heterosis. The most promising early hybrids included GYL 1 × GYL 5 (-4.27%), CM 111 × GYL 4 (-3.56%), GYL 5 × H-07-R-01-3 (-2.49%), and GYL 10 × GYL 11 (-0.36%), which showed significant and favorable standard heterosis over GAYMH 3. These findings align with the studies conducted by Alam *et al*. (2008) [1], Avinashe *et al*. (2013) [9], Matin (2016) [19], Pole *et al*. (2018) [24], Kumar *et al*. (2019) [18], and Tejaswini *et al*. (2023) [32].

The desirable positive heterosis is associated with plant height. The heterobeltiosis (shown in Table 2) varied from-15.85% (GYL 10 × GYL 11) to 21.15% (GYL 1 × GYL 10). Out of the 28 hybrids studied, thirteen hybrids displayed significant positive heterobeltiosis for this trait. The top three hybrids were GYL 1 × GYL 10 (21.15%), CM 111 × GYL 1 (20.58%), and CM 111 × GYL 11 (19.86%), all demonstrating significant heterosis in a favorable direction over their respective better parent. The standard heterosis for plant height (Table 2) ranged from-24.36% (GYL 11 × H-07-R-01-3) to 38.85% (GYL 1 × GYL 10) compared to the check hybrid (GAYMH 3). Among the 28 hybrids, fifteen exhibited significant positive standard heterosis; the top three hybrid combinations were GYL 1 × GYL 10 (38.85%), CM 111 × GYL 1 (38.20%), and GYL 4 × GYL 10 (37.32%). These findings align with the research of Bajaj *et al*. (2007) [10], Saidaiah *et al*. (2008) [27], Sundararajan and Kumar (2011) [30], Matin (2016) [19], Hasan *et al*. (2019) [15] and Patel *et al*. (2019) [21].

Negative heterotic effects are preferred for cob height. The better parent heterosis (Table 2) varied from-17.84% (GYL 11 × H-07-R-01-3) to 22.88% (CM 212-2 × GYL 4). Among the 28 hybrids, eight exhibited negative significance and showed desirable heterobeltiosis. The leading hybrids based on better parent analysis were GYL 11 × H-07-R-01-3 (-17.84%), GYL 10 × H-07-R-01-3 (-16.39%), and GYL 4 × H-07-R-01-3 (-13.71%). The range for standard heterosis (Table 2) was from-26.17% (GYL 11 × H-07-R-01-3) to 56.85% (CM 212-2 × GYL 4). Out of 28 hybrids, five were found to be negatively significant. The top hybrids with the lowest standard heterosis for cob height included GYL 11 × H-07-R-01-3 (-26.17%), GYL 1 × H-07-R-01-3 (-21.49%), and GYL 5 × H-07-R-01-3 (-20.10%). Similar conclusions were drawn by Bajaj *et al*. (2007) [10], Saidaiah *et al*. (2008) [27], Shete *et al*. (2011) [29], Rajesh *et al*. (2014) [26], Matin (2016) [19], Sandesh *et al*. (2018) [28], Kumar *et al*. (2019) [18] and Patel *et al*. (2019) [21].

Positive heterosis is advantageous for cob length. The variation for heterobeltiosis (Table 2) ranged from-10.12% (GYL 10 × H-07-R-01-3) to 31.08% (GYL 4 × GYL 5). In terms of standard heterosis, the range of variation varied from-29.22% (GYL 10 × H-07-R-01-3) to 10.63% (CM 111 × GYL 1) among hybrids. The highest significant and favorable (positive) heterobeltiosis (Table 2) was observed in the cross with 31.08% (GYL 4 × GYL 5), followed by 30.84% (CM 212-2 × GYL 1), 25.90% (GYL 4 × GYL 10) and 25.70% (GYL 1 × GYL 10). None of the crosses exhibited significant and positive standard heterosis. These findings align with the research of Bajaj *et al*. (2007) [11], Saidaiah *et al*. (2008) [27], Amiruzzaman *et al*. (2010) [4], Shete *et al*. (2011) [29], Sundararajan and Kumar (2011) [30], Bekele and Rao (2013) [11], Rajesh *et al*. (2014) [26], Hasan *et al*. (2019) [15], Patel *et al*. (2019) [21], and Al-Jubouri *et al*. (2024) [3].

The desirable positive heterosis is beneficial for cob girth. The range of variation for heterobeltiosis (refer to Table 3) was from-8.57% (GYL 11 × H-07-R-01-3) to 17.77% (CM 111 × GYL 5). In contrast, the standard heterosis variation spectrum ranged from-18.69% (GYL 5 × GYL 11) to 8.59% (CM 111 × GYL 1) in hybrids. The highest significant and favorable (positive) heterobeltiosis (Table 3) was observed in the cross yielding 17.77% (CM 111 × GYL 5), followed closely by 17.47% (CM 111 × GYL 11), 15.29% (CM 111 × CM 212-2), and 14.94% (CM 212-2 × GYL 4). None of the crosses exhibited significant positive standard heterosis. The findings were consistent with those of Bajaj *et al*. (2007) [10], Uddin *et al*. (2008) [33], Amiruzzaman *et al*. (2010) [4], Shete *et al*. (2011) [29], Sundararajan and Kumar (2011) [30], Bekele and Rao (2013) [11], Rajesh *et al*. (2014) [26], Patel *et al*. (2019) [21], Tejaswini *et al*. (2023) [32], and Al-Jubouri *et al*. (2024) [3].

The presence of positive heterosis is advantageous for cob weight. The heterobeltiosis ranged from-13.88% (CM 111 × GYL 5) to 15.64% (GYL 4 × GYL 5) as shown in Table 3. Among the 28 hybrids studied, three hybrids demonstrated significant positive heterobeltiosis for this characteristic, specifically GYL 4 × GYL 5 (15.64%), CM 212-2 × GYL 4 (14.82%), and CM 111 × GYL 1 (12.21%). The standard heterosis, as detailed in Table 3, varied from-50.20% (GYL 10 × H-07-R-01-3) to 16.17% (CM 111 × GYL 1) compared to the check hybrid. Within the 28 hybrids, three hybrids showed significant positive standard heterosis for this characteristic, namely CM 111 × GYL 1 (16.17%), GYL 4 × GYL 5 (12.80%), and CM 212-2 × GYL 4 (11.99%). Comparable findings regarding cob weight have been reported by Rajesh *et al*. (2014) [26], Hasan *et al*. (2019) [15], Kumar *et al*. (2019) [18], Patel *et al*. (2019) [21], Al-Falahy *et al*. (2020) [2], and Nyomayire *et al*. (2021) [20].

Positive heterosis is favored for the number of rows per cob. The variation for heterobeltiosis (Table 3) exhibited a range from-14.53% (CM 212-2 × GYL 10) to 26.47% (CM 111 × GYL 1). In contrast, the variation for standard heterosis ranged from-20.63% (GYL 10 × GYL 11) to 7.14% (CM 212-2 × GYL 4) among hybrids. The most significant and favorable (positive) heterobeltiosis (Table 3) was observed in the cross with 26.47% (CM 111 × GYL 1), followed by 25.00% (CM 212-2 × GYL 4) and 14.81% (GYL 4 × GYL 11). None of the crosses exhibited significant and positive standard heterosis. These findings align closely with the studies conducted by Rajesh *et al*. (2014) [26], Hasan *et al*. (2019) [15], Patel *et al*. (2019) [21], Tejaswini *et al*. (2023) [32], and Al-Jubouri *et al*. (2024) [3].

Table 2: Estimates of Heterobeltiosis (HB) and Standard heterosis (SH) for days to 50 percent tasseling, days to 50 percent silking, days to maturity, plant height, cob height and cob length in maize

Sr. no.	Crosses	Days to 50 percent tasseling		Days to 50 percent silking		Days to maturity		Plant height		Cob height		Cob length	
		HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)
1	CM 111 × CM 212-2	-3.94**	16.77**	-0.48	12.43**	0.00	3.20**	17.69**	11.67**	20.59**	40.55**	14.08*	3.04
2	CM 111 × GYL 1	-5.26**	7.78**	0.00	5.95**	3.58**	2.85**	20.58**	38.20**	4.24	21.49**	22.48**	10.63
3	CM 111 × GYL 4	-12.11**	0.00	-1.53	4.32**	-2.87**	-3.56**	5.87*	22.75**	2.92	31.37**	15.76*	4.55
4	CM 111 × GYL 5	-13.78**	1.20	-12.24**	-7.03**	3.87**	4.98**	6.36	0.93	1.41	18.20**	9.87	-0.76
5	CM 111 × GYL 10	-7.77**	6.59**	-4.52**	2.70*	8.93**	8.54**	18.50**	25.85**	9.07*	27.12**	14.50*	3.42
6	CM 111 × GYL 11	-9.76**	10.78**	-4.27**	9.19**	1.37	5.34**	19.86**	13.73**	1.64	18.46**	15.55*	4.36
7	CM 111 × H-07-R-01-3	-16.26**	1.80	-6.25**	5.41**	0.34	4.63**	10.86**	5.19	-7.06*	8.32*	1.68	-8.16
8	CM 212-2 × GYL 1	-3.94**	16.77**	-10.53**	1.08	-0.69	2.49*	15.14**	31.96**	7.11	16.20**	30.84**	6.26
9	CM 212-2 × GYL 4	-4.43**	16.17**	-3.83**	8.65**	0.34	3.56**	6.01*	22.91**	22.88**	56.85**	19.82**	0.95
10	CM 212-2 × GYL 5	-8.87**	10.78**	-10.53**	1.08	-2.76**	0.36	1.27	-10.14**	1.84	10.49*	10.00	-8.16
11	CM 212-2 × GYL 10	-14.78**	3.59**	-15.31**	-4.32**	-3.10**	0.00	-12.09**	-6.64*	-6.87	1.04	1.93	-19.73**
12	CM 212-2 × GYL 11	-11.71**	8.38**	-7.11**	5.95**	-1.03	2.85**	3.23	-14.98**	-11.42**	-3.90	-2.41	-23.15**
13	CM 212-2 × H-07-R-01-3	-13.30**	5.39**	-11.48**	0.00	-3.41**	0.71	0.88	-16.91**	-10.38**	-2.77	7.25	-15.75**
14	GYL 1 × GYL 4	-16.02**	-8.98**	-13.23**	-11.35**	4.10**	-0.71	14.10**	32.29**	-8.35*	16.98**	13.06*	-4.74
15	GYL 1 × GYL 5	-14.80**	0.00	-10.36**	-6.49**	-5.28**	-4.27**	-3.90	10.14**	-3.94	-11.18**	16.36*	-2.85
16	GYL 1 × GYL 10	-10.36**	3.59**	-4.52**	2.70*	-1.07	-1.42	21.15**	38.85**	5.69	6.15	25.70**	2.09
17	GYL 1 × GYL 11	-16.59**	2.40	-12.32**	0.00	-2.40*	1.42	-6.25*	7.45*	5.69	-5.03	20.56**	-2.09
18	GYL 1 × H-07-R-01-3	-18.72**	-1.20	-11.06**	0.00	0.00	4.27**	-14.30**	-1.77	-2.16	-21.49**	1.17	-17.84**
19	GYL 4 × GYL 5	-7.14**	8.98**	-1.55	2.70*	2.46*	3.56**	16.67**	35.27**	2.04	30.24**	31.08**	10.44
20	GYL 4 × GYL 10	1.04	16.77**	2.51*	10.27**	6.79**	6.41**	18.44**	37.32**	17.45**	49.91**	25.90**	6.07
21	GYL 4 × GYL 11	-7.80**	13.17**	-12.32**	0.00	-2.40*	1.42	10.94**	28.62**	7.74*	37.52**	16.67*	-1.71
22	GYL 4 × H-07-R-01-3	-15.27**	2.99*	-3.37**	8.65**	4.44**	8.90**	-5.59	9.46**	-13.71**	10.14*	7.88	-9.11
23	GYL 5 × GYL 10	-15.82**	-1.20	-13.07**	-6.49**	3.87**	4.98**	-1.02	5.11	-5.69	-5.29	7.50	-10.25
24	GYL 5 × GYL 11	-12.20**	7.78**	-18.48**	-7.03**	1.71	5.69**	-2.36	-13.37**	-0.09	-7.63	2.73	-14.23*
25	GYL 5 × H-07-R-01-3	-19.70**	-2.40	-12.5**	-1.62	-6.48**	-2.49*	-5.40	-16.06**	-13.59**	-20.10**	-6.59	-22.01**
26	GYL 10 × GYL 11	-19.51**	-1.20	-11.37**	1.08	-4.11**	-0.36	-15.85**	-10.63**	-6.64	-6.24	-3.37	-23.91**
27	GYL 10 × H-07-R-01-3	-21.18**	-4.19**	-18.75**	-8.65**	-0.68	3.56**	-12.02**	-6.56*	-16.39**	-16.03**	-10.12	-29.22**
28	GYL 11 × H-07-R-01-3	-14.63**	4.79**	-15.64**	-3.78**	-3.75**	0.36	-5.67	-24.36**	-17.84**	-26.17**	-7.95	-27.51**
S. E.±		0.71		0.78		0.92		5.43		3.13		0.96	
Range	Min.	-21.18	-8.98	-18.75	-11.35	-6.48	-4.27	-15.85	-24.36	-17.84	-26.17	-10.12	-29.22
	Max.	1.04	16.77	2.51	12.43	8.93	8.90	21.15	38.85	22.88	56.85	31.08	10.63
Significant and positive crosses		0	17	1	12	8	16	13	15	5	15	14	0
Significant and negative crosses		27	2	23	8	10	3	5	9	8	5	0	9
Total no. of significant crosses		27	19	24	20	18	19	18	24	13	20	14	9

*, ** Significant at P = 0.05 and P = 0.01 levels of probability, respectively, BP: Better parent, SC: Standard heterosis over check variety GAYMH 3

Table 3: Estimates of Heterobeltiosis (HB) and Standard heterosis (SH) for cob girth, cob weight, number of rows per cob, number of grains per row, shelling percentage,100-grain weight and grain yield per plant in maize

Sr. No.	Crosses	Cob girth		Cob weigh		Number of rows per cob		Number of grains per row		Shelling percentage		100-grain weight		Grain yield per plant	
		HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	..HB (%)	SH (%)
1	CM 111 × CM 212-2	15.29**	-1.01	-8.49	-5.27	12.38	-6.35	4.07	0.59	13.42**	0.04	-4.46	-16.04**	29.49*	-7.01
2	CM 111 × GYL 1	8.86	8.59	12.21*	16.17**	26.47**	2.38	10.96**	11.39**	18.25**	6.84**	12.39*	9.27	36.95**	-1.65
3	CM 111 × GYL 4	8.91	-4.29	5.47	9.19	2.78	-11.90*	-4.34	8.25*	-5.12	-7.94**	5.77	1.99	7.84	26.39**
4	CM 111 × GYL 5	17.77**	-1.26	-13.88*	-10.84	8.49	-8.73	-5.49	-8.64*	-3.90	-11.38**	6.56	-6.36	5.23	-24.44**
5	CM 111 × GYL 10	13.69*	-3.54	-12.32*	-9.22	10.26	2.38	7.78*	11.59**	3.45	-8.75**	9.50	-3.78	34.59**	-3.35
6	CM 111 × GYL 11	17.47**	-1.52	-13.77*	-10.73	6.73	-11.90*	4.62	6.88	4.41	-7.90**	8.51	-4.65	20.86	-13.21
7	CM 111 × H-07-R-01-3	10.65*	7.58	-11.09	-7.96	7.69	0.00	-4.11	5.50	1.58	-6.92**	11.25	-2.24	13.72	-18.34*
8	CM 212-2 × GYL 1	5.06	4.80	5.81	-12.57*	11.43	-7.14	2.54	2.95	12.82**	1.93	-5.28	-7.91	62.42**	-9.51
9	CM 212-2 × GYL 4	14.94**	1.01	14.82*	11.99*	25.00**	7.14	-3.30	9.43*	13.3**	9.92**	-4.33	-7.75	16.54*	36.59**
10	CM 212-2 × GYL 5	2.35	-12.12**	2.08	-34.49**	5.66	-11.11*	-2.41	-20.43**	-10.59**	-17.55**	-17.35**	-27.66**	19.61	-33.36**
11	CM 212-2 × GYL 10	2.35	-12.12**	4.55	-44.75**	-14.53*	-20.63**	-11.01**	-7.86	-5.02	-17.83**	-17.17**	-31.1**	21.59	-32.26**
12	CM 212-2 × GYL 11	-3.82	-17.42**	2.97	-45.02**	-2.86	-19.05**	-12.69**	-10.81**	-9.6**	-21.78**	-19.18**	-32.25**	7.31	-40.22**
13	CM 212-2 × H-07-R-01-3	-4.68	-7.32	3.80	-45.14**	-3.42	-10.32	-13.04**	-4.32	-4.37	-12.37**	-16.11**	-27.35**	7.09	-40.34**
14	GYL 1 × GYL 4	5.32	5.05	7.07	4.43	-3.70	-17.46**	-4.69	7.86	-4.99	-7.82**	3.68	0.80	-9.66	5.88
15	GYL 1 × GYL 5	-3.29	-3.54	-5.41	-21.84**	1.89	-14.29**	-1.96	-1.57	-1.82	-9.47**	-2.20	-4.92	31.39	-33.57**
16	GYL 1 × GYL 10	8.35	8.08	-1.88	-18.93**	5.13	-2.38	3.23	6.88	-4.78	-13.96**	1.87	-0.96	46.65**	-20.80*
17	GYL 1 × GYL 11	1.52	1.26	-8.41	-24.32**	7.69	-11.11*	0.00	2.16	-4.05	-13.30**	1.42	-1.39	29.12	-35.72**
18	GYL 1 × H-07-R-01-3	5.32	5.05	-6.67	-22.89**	0.00	-7.14	7.68*	18.47**	-0.09	-8.45**	-4.23	-6.89	29.01	-35.78**
19	GYL 4 × GYL 5	12.93*	-0.76	15.64*	12.80*	10.19	-5.56	-3.82	8.84*	14.65**	11.23**	10.40*	6.46	14.04	33.66**
20	GYL 4 × GYL 10	14.08**	0.25	4.60	2.02	9.40	1.59	-5.73	6.68	-1.14	-4.09	8.75	4.86	18.00*	38.30**
21	GYL 4 × GYL 11	10.92*	-2.53	-5.11	-7.45	14.81*	-1.59	2.08	15.52**	-1.09	-4.04	4.39	0.66	-4.02	12.50
22	GYL 4 × H-07-R-01-3	7.53	4.55	-7.66	-9.93	11.11	3.17	1.56	14.93**	3.65	0.56	3.71	0.01	-4.78	11.60
23	GYL 5 × GYL 10	6.25	-9.85*	-5.10	-39.10**	-10.26	-16.67**	-11.20**	-8.06*	-13.53**	-20.26**	-5.74	-17.5**	20.36	-35.00**
24	GYL 5 × GYL 11	-0.62	-18.69**	-7.64	-40.73**	0.00	-15.87**	-12.31**	-10.41*	-16.06**	-22.60**	-6.94	-18.55**	21.37	-38.63**
25	GYL 5 × H-07-R-01-3	-7.53	-10.10*	-11.84	-43.43**	-5.13	-11.90*	-17.86**	-9.63*	-8.92**	-16.01**	-6.76	-18.39**	21.56	-38.53**
26	GYL 10 × GYL 11	-3.57	-18.18**	-1.16	-47.22**	-14.53*	-20.63**	-5.50	-2.16	-11.74**	-31.50**	-4.09	-19.6**	7.35	-42.03**
27	GYL 10 × H-07-R-01-3	-5.19	-7.83	-0.81	-50.20**	-1.71	-8.73	-8.39*	0.79	-12.86**	-20.15**	-10.23	-22.27**	13.12	-38.91**
28	GYL 11 × H-07-R-01-3	-8.57	-11.11*	-4.49	-49.00**	-7.69	-14.29**	-10.54**	-1.57	-17.37**	-24.28**	-6.18	-18.75**	15.42	-43.63**
S. E.±		0.59		5.85		0.88		1.37		1.98		1.14		7.89	
Range	Min.	-8.57	-18.69	-13.88	-50.20	-14.53	-20.63	-17.86	-20.43	-17.37	-31.50	-19.18	-32.25	-9.66	-43.63
	Max.	17.77	8.59	15.64	16.17	26.47	7.14	10.96	18.47	18.25	11.23	12.39	9.27	62.42	38.30
Significant and positive crosses		9	0	3	3	3	0	3	8	5	3	2	0	7	4
Significant and negative crosses		0	8	3	15	2	13	8	6	8	20	4	11	0	16
Total no. of significant crosses		9	8	6	18	5	13	11	14	13	23	6	11	7	20

*, ** Significant at P = 0.05 and P = 0.01 levels of probability, respectively, BP: Better parent, SC: Standard heterosis over check variety GAYMH 3

The presence of positive heterosis is advantageous for the number of grains produced per row. The variability range for heterobeltiosis, as shown in Table 3, varied from-17.86% (GYL 5 × H-07-R-01-3) to 10.96% (CM 111 × GYL 1). In contrast, the spectrum for standard heterosis ranged from-20.43% (CM 212-2 × GYL 5) to 18.47% (GYL 1 × H-07-R-01-3) across hybrids. The highest statistically significant and favorable (positive) heterobeltiosis noted in the study was 10.96% for the combination (CM 111 × GYL 1), followed by 7.78% (CM 111 × GYL 10) and 7.68% (GYL 1 × H-07-R-01-3). The highest significant and beneficial (positive) standard heterosis recorded was 18.47% for the combination (GYL 1 × H-07-R-01-3), succeeded by 15.52% (GYL 4 × GYL 11) and 14.93% (GYL 4 × H-07-R-01-3). These results were similar with Uddin *et al*. (2008) [33], Rajesh *et al*. (2014) [26], Pole *et al*. (2018) [24], Patel *et al*. (2019) [21], Al-Falahy *et al*. (2020) [2], Tejaswini *et al*. (2023) [32] and Al-Jubouri *et al*. (2024) [3].

The shelling percentage, defined as the ratio of seed yield to cob weight, signifies that an increase in shelling percentage enhances seed weight recovery, contributing positively to the overall yield. The measurements of better parent heterosis (refer to Table 3) varied between-17.37% (GYL 11 × H-07-R-01-3) and 18.25% (CM 111 × GYL 1). Five hybrid combinations demonstrated significant and positive heterosis concerning this trait. The most significant hybrids exhibiting the highest shelling percentages were CM 111 × GYL 1 (18.25%), GYL 4 × GYL 5 (14.65%), CM 111 × CM 212-2 (13.42%), and CM 212-2 × GYL 4 (13.30%). The three hybrid combinations exhibited considerable positive heterosis when compared to their respective standard heterosis. The Standard heterosis (refer to Table 3) for shelling percentage exhibited a range from-31.50% (GYL 10 × GYL 11) to 11.23% (GYL 4 × GYL 5). The top-performing hybrids were GYL 4 × GYL 5 (11.23%), followed by CM 212-2 × GYL 4 (9.92%) and CM 111 × GYL 1 (6.84%). These findings align with the results of Shete *et al*. (2011) [29], Sandesh *et al*. (2018) [28], Kumar *et al*. (2019) [18], Al-Falahy *et al*. (2020) [2], Tejaswini *et al*. (2023) [32], and Al-Jubouri *et al*. (2024) [3].

The weight of 100 grains is also considered important as a higher test weight contributes to increased seed yield, making this trait desirable. Two crosses showed significant and positive better parent heterosis. The relative heterosis percentages (see Table 3) ranged from-19.18% (CM 212-2 × GYL 11) to 12.39% (CM 111 × GYL 1). The highest 100-grain weight was recorded in the hybrid CM 111 × GYL 1 (12.39%), followed by GYL 4 × GYL 5 (10.40%). Standard heterosis (refer to Table 3) varied from-32.25% (CM 212-2 × GYL 11) to 9.27% (CM 111 × GYL 1). None of the crosses exhibited significant and positive standard heterosis. The findings regarding 100-grain weight align with those of Bajaj *et al*. (2007) [10], Uddin *et al*. (2008) [33], Saidaiah *et al*. (2008) [27], Amiruzzaman *et al*. (2010) [4], Shete *et al*. (2011) [29], Sundararajan and Kumar (2011) [30], Asif *et al*. (2014) [8], Rajesh *et al*. (2014) [26], Pole *et al*. (2018) [24] and Patel *et al*. (2019) [21].

The most crucial character is grain yield, which is preferable in a positive direction. The data indicated that the degree of better parent heterosis (Table 3) varied from-9.66% (GYL 1 × GYL 4) to 62.42% (CM 212-2 × GYL 1). Out of 28 crosses, seven exhibited positive and significant heterosis. The most remarkable hybrids based on the better parent were CM 212-2 × GYL 1 (62.42%), GYL 1 × GYL 10 (46.65%), CM 111 × GYL 1 (36.95%), and CM 111 × GYL 10 (34.59%). The range of standard heterosis values (Table 3) varied from-43.63% (GYL 11 × H-07-R-01-3) to 38.30% (GYL 4 × GYL 10). Among the 28 hybrids, four were found to have positive and significant standard heterosis. The top hybrids in terms of grain yield per plant were GYL 4 × GYL 10 (38.30%), followed by CM 212-2 × GYL 4 (36.59%), GYL 4 × GYL 5 (33.66%), and CM 111 × GYL 4 (26.39%). Same results were reported by Araujo and Filho (2001) [7], Unay *et al*. (2004) [33], Izhar and Chakraborty (2013) [16], Asif *et al*. (2014) [8], El-Shamarka *et al*. (2015) [13], Prafulla (2015) [25], Patel and Kathiria (2016) [22], Talukder *et al*. (2016) [31], Patil *et al*. (2017) [23], Karim *et al*. (2018) [17], Pole *et al*. (2018) [24], Sandesh *et al*. (2018) [28], Patel *et al*. (2019) [21], Al-Falahy *et al*. (2020) [2], Bisen *et al*. (2020) [12], Nyomayire *et al*. (2021) [20], Gurjar *et al*. (2022) [14] and Al-Jubouri *et al*. (2024) [3].

Conclusion

From ongoing discussion, it could be concluded that the best three promising crosses namely CM 212-2 × GYL 1, GYL 1 × GYL 10 and CM 111 × GYL 1 exhibited high significant and positive heterobeltiosis, while GYL 4 × GYL 10, CM 212-2 × GYL 4 and GYL 4 × GYL 5 exhibited high standard heterosis in desired direction for grain yield per plant and some other yield attributing traits. Therefore, these three best crosses could be further evaluated over years and locations to exploit for commercial cultivation through heterosis breeding or utilized in future breeding programme to obtain desirable transgressive segregants and to identify high yielding superior inbreds.

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