Agronomic Performance, Combining Ability, and Heterosis of 20 Single-Cross Maize Hybrids

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Abstract

Maize (Zea mays L.) is an important cereal crop, and developing high-yielding single-cross hybrids is essential to improve productivity. This study evaluated agronomic performance, yield components, broad-sense heritability, general combining ability (GCA), specific combining ability (SCA), reciprocal effects, heterosis, heterobeltiosis, and standard heterosis of 20 single-cross maize hybrids derived from five inbred parents. The experiment was conducted in Koto Tingga Village, Padang City, Indonesia, from November 2024 to February 2025, using a randomized block design with three replications, 20 hybrids, five inbred parents, and P32 as a check. Data were analyzed using analysis of variance, Tukey's HSD at 5%, and a fixed-model full diallel analysis (Griffing Method I). Genotypes significantly affected 14 of 16 traits; ear height and stem diameter were not significant. Broad-sense heritability of yield potential was 77.79%. GCA was highly significant for 14 traits and SCA was significant for nine traits; reciprocal effects were significant only for ear length. Mz2 had the highest GCA for yield potential (0.85), and Mz2 × Mz4 had the highest SCA for yield potential (1.61). HUA16 and HUA6 had the highest estimated yield potentials (13.75 and 13.73 t ha^{-1}), although neither differed significantly from P32 by Tukey's HSD at 5%. They showed heterosis of 36.03% and 35.86%, heterobeltiosis of 29.35% and 29.19%, and positive standard heterosis relative to P32 of 15.32% and 15.18%, respectively. HUA16 and HUA6 are promising candidates for further yield and multi-location testing.

Keywords: *Combining ability, griffing method I, heterobeltiosis, heterosis, single-cross hybrid.*

INTRODUCTION

Maize (Zea mays L.) is one of the most important cereal crops used as food, feed, and industrial raw material. Erenstein et al. (2022) stated that maize plays a major role in global production and trade because of its wide utilization. In Indonesia, Syahruddin et al. (2020) reported that maize production improvement remains an important part of crop breeding and food crop development programs. Therefore, developing high-yielding superior varieties is essential to support productivity improvement and national seed self-sufficiency.

Hybrid variety development is one of the main approaches to increasing maize productivity. According to Labroo et al. (2021), heterosis is a fundamental basis of hybrid breeding because it can improve plant vigor, growth, and yield performance. Suwarno et al. (2023) also explained that single-cross hybrids are derived from crosses between two inbred lines and usually show superiority over their parents. The success of hybrid development is strongly determined by the quality of inbred parents, the suitability of cross combinations, and agronomic traits that support yield performance.

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Maize yield is a complex quantitative trait because it is influenced by several yield components and environmental conditions. Al-Rawi et al. (2024) stated that maize grain yield is associated with several supporting traits, so selection should not rely only on final yield. Traits such as ear length, ear diameter, number of kernel rows, number of kernels per row, kernel weight, and 1000-kernel weight need to be considered in genotype selection. Fadhli et al. (2025) further emphasized that heritability and trait association information can help breeders determine effective selection criteria for identifying high-productivity maize genotypes.

In addition to phenotypic evaluation, hybrid selection needs to be supported by genetic information through combining ability and heterosis analysis. Suyadi et al. (2021) reported that general combining ability, specific combining ability, and reciprocal effects are important in evaluating Indonesian tropical maize. Ali et al. (2025) also emphasized that the success of hybrid maize breeding depends on understanding the combining ability of inbred lines and heterotic effects. General combining ability reflects the average performance of a parent in various cross combinations, whereas specific combining ability indicates the superiority of a particular cross combination.

Our previous study primarily evaluated the seed production performance of 20 single-cross maize hybrid combinations based on ear and yield-related traits (Hidayatullah et al., 2025). However, the genetic basis underlying their performance, including broad-sense heritability, parental general combining ability, specific combining ability, reciprocal effects, and heterotic expression, was not evaluated. The present study therefore extends the previous evaluation by elucidating the genetic contributions and parental combinations associated with superior hybrid performance. Accordingly, this study aimed to evaluate agronomic performance, yield components, yield potential, broad-sense heritability, general combining ability, specific combining ability, reciprocal effects, heterosis, heterobeltiosis, and standard heterosis in 20 single-cross maize hybrids derived from five inbred parents.

MATERIALS AND METHODS

Place and Time

The research was conducted from November 2024 to February 2025 in an experimental field in Koto Tingga Village, Pauh District, Padang City, West Sumatra Province, Indonesia (Latitude: 0°55'56.57"S Longitude**:** 100°24'50.07" E). The experimental site was located at an altitude of approximately 75 m above sea level.

Materials and Tools

The planting material used was 26 genotypes, consisting of 20 new single-cross hybrid genotypes, five parental inbreds, and one P32 reference hybrid. The tools used included a hand tractor, rotary engine, sprayer, hoe, measuring tape, watering can, calipers, analytical balance, grain moisture tester, stationery, and labels. The genetic material of the study is presented in Table 1.

Research Design

The study was arranged in a randomized block design with one factor, namely genotype, with three replications. The treatments consisted of 26 genotypes, resulting in 78 experimental units. Each experimental plot measured 1 m × 2 m and consisted of two rows of plants. The planting distance used was 75 cm between rows and 20 cm within rows. Each planting hole was filled with two seeds, then thinned to leave one plant per hole, resulting in 20 plants per plot.

Research Implementation

The land was thoroughly tilled to a depth of approximately 20 cm, then plots were created according to the experimental size. Planting was carried out using a ditch system at a depth of 3–5 cm. Fertilization was applied twice: at 14 days after planting (DAP) using NPK 16-16-16 and urea at 250 kg ha^{-1} and 150 kg ha^{-1}, respectively, and at the age of 30 DAP using NPK 16-16-16 and urea at 100 kg ha^{-1} and 200 kg ha^{-1}, respectively. Plant maintenance included watering, replanting, thinning, weeding, and pest and disease control according to field conditions. Harvesting was carried out when the plants reached physiological maturity.

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Table 1. Research Planting Materials

No.	Hybrid Code	Female	Male	Description
1	HUA1	Mz2	Mz1	Single cross hybrid
2	HUA2	Mz3	Mz1	Single cross hybrid
3	HUA3	Mz4	Mz1	Single cross hybrid
4	HUA4	Mz5	Mz1	Single cross hybrid
5	HUA5	Mz3	Mz2	Single cross hybrid
6	HUA6	Mz4	Mz2	Single cross hybrid
7	HUA7	Mz5	Mz2	Single cross hybrid
8	HUA8	Mz4	Mz3	Single cross hybrid
9	HUA9	Mz5	Mz3	Single cross hybrid
10	HUA10	Mz5	Mz4	Single cross hybrid
11	HUA11	Mz4	Mz5	Single cross hybrid
12	HUA12	Mz3	Mz5	Single cross hybrid
13	HUA13	Mz2	Mz5	Single cross hybrid
14	HUA14	Mz1	Mz5	Single cross hybrid
15	HUA15	Mz3	Mz4	Single cross hybrid
16	HUA16	Mz2	Mz4	Single cross hybrid
17	HUA17	Mz1	Mz4	Single cross hybrid
18	HUA18	Mz2	Mz3	Single cross hybrid
19	HUA19	Mz1	Mz3	Single cross hybrid
20	HUA20	Mz1	Mz2	Single cross hybrid
21	Mz1	-	-	Inbred parents
22	Mz2	-	-	Inbred parents
23	Mz3	-	-	Inbred parents
24	Mz4	-	-	Inbred parents
25	Mz5	-	-	Inbred parents
26	P32	-	-	Check hybrid

Research Parameters

The parameters observed included plant height, ear height, stem diameter, days to 50% anthesis, days to 50% silking, harvest age, ear length, ear diameter, number of kernel rows per ear, number of kernels per row, ear weight with husk, ear weight without husk, kernel weight per ear, harvest moisture content, 1000-kernel weight, and yield potential.

Data Analysis

Observational data were analyzed using analysis of variance based on a Randomized Block Design (RBD). If the analysis of variance results indicated a significant genotype effect, the analysis was continued with the Tukey's HSD test at the 5% level to determine differences between genotypes. Broad-sense heritability values were estimated based on the genotype and phenotype variance components.

Combining ability analysis was conducted using the Griffing Method I full diallel approach with a fixed model. This analysis involved five inbred parents: Mz1, Mz2, Mz3, Mz4, and Mz5, and 20 F1 hybrid combinations, including their reciprocal crosses with three replications. The reference hybrid P32 was not included in the diallel analysis as it was used solely as a reference variety.

Heterosis was calculated based on the comparison of the F1 hybrid value to the average of its two parents, while heterobeltiosis was calculated based on the comparison of the F1 hybrid value to the best parent. Standard heterosis was calculated by comparing each F1 hybrid with the P32 check hybrid.

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RESULTS AND DISCUSSION

Agronomic Performance and Yield Components

Analysis of variance showed significant or highly significant genotype effects on 14 of the 16 observed traits. Only ear height and stem diameter were not significantly affected by genotype (Table 2). Plant height and flowering and harvest ages showed significant effects, whereas ear and yield-related traits, harvest moisture content, 1000-kernel weight, and yield potential showed highly significant effects.

The coefficient of variation ranged from 1.60% to 10.02%, suggesting acceptable precision for evaluating agronomic and yield-related traits. Broad-sense heritability based on genotype means was high for plant height and most yield-related traits, including yield potential (77.79%).

Table 2. Significance Level, Coefficient of Variation, and Broad-Sense Heritability of Agronomic Traits, Yield Components, and Yield Potential

Parameter	Significance	CV (%)	H^2bs (%)
Plant height	*	5.58	52.16
Ear height	ns	8.58	22.69
Stem diameter	ns	7.39	10.64
50% anthesis	*	3.09	53.57
50% silking	*	3.01	49.44
Harvest age	*	1.60	43.57
Ear length	**	5.24	89.77
Ear diameter	**	2.68	82.40
Number of kernel rows per ear	**	3.85	87.23
Number of kernels per row	**	5.18	90.27
Ear weight with husk	**	9.42	88.36
Ear weight without husk	**	9.29	88.70
Kernel weight per ear	**	8.93	89.12
Harvest moisture content	**	3.72	86.16
1000-kernel weight	**	6.33	82.26
Yield potential	**	10.02	77.79

Note: ns = not significant; * = significant at 5%; ** = significant at 1%; CV = coefficient of variation; H^2bs = broad-sense heritability. Broad-sense heritability was calculated based on genotype means.

The significance pattern in Table 2 indicates detectable genotypic differences in plant height, flowering and harvest ages, and reproductive and yield-related traits, whereas ear height and stem diameter were not significant. Most yield components showed highly significant genotype effects. These findings support selection based on reproductive and yield-related traits in this environment. Similar patterns of genotypic variation in agronomic and yield traits have been reported for maize (Magar et al., 2021; Al-Rawi et al., 2024).

The coefficient of variation ranged from 1.60% for harvest age to 10.02% for yield potential. Broad-sense heritability based on genotype means was high for plant height (52.16%), ear length (89.77%), ear weight with husk (88.36%), ear weight without husk (88.70%), kernel weight per ear (89.12%), and yield potential (77.79%), among other traits. These estimates suggest substantial genotypic contributions to variation among genotype means within this experimental environment. Genetic diversity and heritability are important considerations when identifying promising maize materials (Pangestu et al., 2023; Fadhillah et al., 2025).

The mean performance of F1 hybrids showed variation among cross combinations in vegetative, flowering, ear, and yield-related traits. For clarity, the 16 observed traits are presented in two tables. Table 3 presents vegetative, flowering, ear length, and ear diameter traits, whereas Table 4 presents yield components and yield potential.

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Table 3. Mean Performance of Hybrids and Check Genotype for Vegetative, Flowering, Ear Length and Ear Diameter

Hybrid Code	PH	EH	SD	A50	S50	HA	EL	ED
HUA1	239.30	109.93	19.90	53.27	54.00	108.67	14.42	45.18
HUA2	229.30	103.70	19.86	53.33	54.47	109.13	12.73	44.97
HUA3	247.83	113.20	18.39	54.13	54.77	109.43	14.58	46.63
HUA4	243.33	112.63	19.71	52.60	54.03	108.70	14.72	46.09
HUA5	254.03	117.53	21.30	55.73	56.67	111.33	14.65	46.08
HUA6	254.07	111.07	19.82	55.90	56.57	111.23	16.03	48.80
HUA7	264.13	122.23	20.48	55.87	56.50	111.17	15.10	48.02
HUA8	266.53	123.33	21.55	56.37	56.70	111.37	15.98	47.94
HUA9	259.20	118.33	20.49	53.57	54.40	109.07	15.98	47.08
HUA10	249.13	106.30	20.02	58.07	58.60	113.27	15.63	45.45
HUA11	239.93	106.37	19.81	54.73	56.20	110.87	15.38	47.43
HUA12	248.77	112.83	20.37	54.30	55.57	110.23	15.62	46.29
HUA13	242.93	105.60	19.51	54.83	55.83	110.50	16.12	47.41
HUA14	247.70	107.67	19.47	54.53	56.50	111.17	14.27	46.10
HUA15	233.40	97.13	19.43	56.40	57.27	111.93	17.18	48.05
HUA16	247.53	111.17	19.88	55.43	56.90	111.57	15.90	50.69
HUA17	256.10	113.13	19.87	53.30	54.20	108.87	14.40	46.61
HUA18	245.63	112.07	19.82	54.83	55.67	110.33	16.25	46.10
HUA19	227.87	103.67	18.51	53.80	54.73	109.40	14.65	43.34
HUA20	240.13	105.73	20.06	53.50	54.13	108.80	15.82	45.65
Average of parents	246.20	108.31	18.92	54.18	55.27	109.93	13.91	44.67
Average of Hybrids	246.84	110.68	19.91	54.73	55.68	110.35	15.28	46.70
P32	264.03	104.57	18.01	56.93	57.03	111.70	18.50	46.93
HSD 0.05	43.89	29.99	4.61	5.37	5.32	5.62	2.51	3.94

Note: PH = plant height; EH = ear height; SD = stem diameter; A50 = 50% anthesis; S50 = 50% silking; HA = harvest age; EL = ear length; ED = ear diameter; HSD = Tukey's Honest Significant Difference at 5%.

The mean performance presented in Table 3 shows that the tested hybrids had relatively similar vegetative performance, while genotype effects were more evident for flowering and ear traits. This pattern is consistent with the ANOVA results, in which plant height showed a significant genotype effect, whereas ear height and stem diameter were not significantly affected by genotype. Flowering and ear traits also showed significant or highly significant genotypic effects. Among the hybrids, HUA8 showed the highest plant height (266.53 cm), while HUA8 and HUA7 had relatively high ear height. Although plant height showed a significant genotype effect, ear height and stem diameter did not differ significantly among genotypes. Therefore, vegetative traits should be considered alongside yield-related traits rather than used as the primary selection criteria. For flowering and harvest age, HUA4 showed the earliest anthesis, whereas HUA17 and HUA20 tended to have earlier harvest ages. In contrast, HUA10 tended to flower and mature later than most tested hybrids. Early maturity can be useful in hybrid development when the breeding objective is directed toward shorter cropping duration or escape from terminal stress, but it must still be balanced with yield potential.

For ear traits, HUA16 showed the highest ear diameter, followed by HUA6, HUA7, HUA15, and HUA8, while P32 showed the highest ear length. Ear length and ear diameter are important supporting traits because they are associated with kernel arrangement, grain filling capacity, and final yield formation. Previous studies on maize hybrids reported that yield-related traits such as ear length, ear diameter, number of kernel rows, and number of kernels per row are important criteria in identifying high-yielding

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hybrid candidates (Suwarno et al., 2023; Yustisia et al., 2021). In the present study, the relatively large ear diameter of HUA16 and HUA6 may reflect greater physical capacity for kernel development, which could partly contribute to their high yield potential.

Table 4. Mean Performance of Hybrids and Check Genotype for Yield Components and Yield Potential

Hybrid Code	NKRE	NKR	EWH	EWWH	KWE	HM	B1000	YP
HUA1	14.50	32.77	205.45	174.76	134.87	26.47	303.40	11.55
HUA2	14.33	27.73	168.30	144.14	110.88	27.45	305.30	9.41
HUA3	13.30	30.70	216.12	184.15	129.29	26.64	334.17	11.06
HUA4	13.67	30.47	206.54	176.67	128.60	27.81	330.23	10.83
HUA5	13.80	30.63	210.45	182.10	133.67	29.83	339.50	10.96
HUA6	13.60	33.13	267.08	229.35	162.47	27.45	383.57	13.73
HUA7	13.93	30.87	239.97	210.37	147.26	29.92	366.03	12.10
HUA8	13.30	32.27	250.17	211.01	148.37	29.44	375.47	12.25
HUA9	12.93	32.10	240.64	207.09	145.85	28.95	376.80	12.12
HUA10	12.53	30.33	213.93	184.59	123.51	31.23	356.53	9.93
HUA11	13.20	30.10	218.39	187.12	128.87	29.60	345.57	10.60
HUA12	12.93	31.47	218.62	188.00	135.55	29.22	346.47	11.19
HUA13	13.13	33.07	241.38	209.01	146.49	28.71	359.13	12.39
HUA14	13.53	28.93	197.40	170.75	125.03	27.46	344.67	10.56
HUA15	12.60	30.60	238.45	198.97	138.09	28.29	376.57	11.53
HUA16	13.50	32.30	268.92	232.43	161.64	27.11	386.00	13.75
HUA17	13.47	28.33	201.02	173.39	127.55	27.56	350.60	10.78
HUA18	14.60	30.83	212.08	182.69	137.71	27.87	321.13	11.57
HUA19	13.67	27.80	161.42	138.89	110.38	27.32	294.90	9.37
HUA20	14.00	30.53	200.32	170.08	128.78	28.06	321.43	10.81
Average of parents	13.57	27.74	187.26	159.09	115.29	29.26	331.71	9.50
Average of Hybrids	13.53	30.75	218.83	187.78	135.24	28.32	345.87	11.32
P32	15.87	41.37	290.67	247.82	201.81	23.87	320.33	11.92
HSD 0.05	1.67	5.04	64.52	54.51	38.00	3.35	68.85	3.50

Note: NKRE = number of kernel rows per ear; NKR = number of kernels per row; EWH = ear weight with husk; EWWH = ear weight without husk; KWE = kernel weight per ear; HM = harvest moisture content; B1000 = 1000-kernel weight; YP = yield potential; HSD = Tukey's Honest Significant Difference at 5%.

The yield component data in Table 4 further indicate the promising performance of HUA16 and HUA6. HUA16 produced the highest yield potential at 13.75 t ha^{-1}, followed closely by HUA6 at 13.73 t ha^{-1}. These values were numerically higher than that of the P32 check hybrid, which produced 11.92 t ha^{-1}. Among the experimental hybrids, the relatively high yield potential of HUA16 and HUA6 was accompanied by high kernel weight per ear, ear weight without husk, and 1000-kernel weight. HUA16 had kernel weight per ear of 161.64 g and 1000-kernel weight of 386.00 g, while HUA6 had kernel weight per ear of 162.47 g and 1000-kernel weight of 383.57 g. This result suggests that the relatively high yield potential of both hybrids was mainly associated with heavier kernels and better ear productivity rather than with a higher number of kernel rows per ear.

Although P32 showed higher values for several yield components, its numerical yield potential was lower than those of HUA16 and HUA6. This indicates that yield potential was not determined by a single component but by the combined contribution of ear diameter, kernel weight per ear, 1000-kernel weight, harvest moisture content, and overall plant performance. Yield component-based selection has been reported to be effective in maize breeding because grain yield is a complex trait controlled by several

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supporting characters (Yustisia et al., 2021). Because the present evaluation was conducted in a single environment, the promising performance of HUA16 and HUA6 should be validated through multi-location testing. Fadhillah et al. (2025) emphasized that agronomic performance and yield stability across environments should be considered when selecting promising maize hybrids.

General Combining Ability, Specific Combining Ability, and Reciprocal Effects

Diallel analysis was conducted to examine GCA, SCA, and reciprocal effects on the observed traits. F statistics for vegetative, flowering, maturity, and ear dimension traits are presented in Table 5, and those for yield components and yield potential are presented in Table 6.

Table 5. F Statistics for GCA, SCA, and Reciprocal Effects on Vegetative, Flowering, Maturity, and Ear Dimension Traits

Source of Variation	df	PH	EH	SD	A50	S50	HA	EL	ED
GCA	4	4.46^{**}	1.03^{ns}	0.81^{ns}	6.91^{**}	7.06^{**}	6.32^{**}	22.59^{**}	15.33^{**}
SCA	10	1.33^{ns}	0.87^{ns}	1.28^{ns}	0.97^{ns}	0.93^{ns}	0.83^{ns}	6.70^{**}	6.43^{**}
Reciprocal	10	1.47^{ns}	1.72^{ns}	0.86^{ns}	0.93^{ns}	0.80^{ns}	0.71^{ns}	2.58^{*}	1.07^{ns}

Note: PH = plant height; EH = ear height; SD = stem diameter; A50 = 50% anthesis; S50 = 50% silking; HA = harvest age; EL = ear length; ED = ear diameter; GCA = general combining ability; SCA = specific combining ability; ns = not significant; * = significant at 5%; ** = significant at 1%.

The diallel analysis (Table 5) showed highly significant GCA effects on plant height, 50% anthesis, 50% silking, harvest age, ear length, and ear diameter, whereas GCA effects on ear height and stem diameter were not significant. These findings indicate the contribution of combining ability to vegetative, phenological, and ear traits, with trait-specific differences.

SCA had highly significant effects on ear length and ear diameter, but not on the other traits in Table 5. Reciprocal effects were significant for ear length only; reciprocal effects on plant height, ear height, stem diameter, flowering time, harvest age, and ear diameter were not significant. The significance for ear length suggests that crossing direction may affect this trait in the tested parental combinations.

The simultaneous significance of GCA and SCA for ear length and ear diameter indicates that both additive and non-additive genetic effects contributed to the expression of these traits. Similar findings have shown that maize hybrid improvement should consider both parental combining ability and specific cross performance when selecting for ear-related characteristics (Suyadi et al., 2021; Ali et al., 2025). The corresponding diallel analysis for yield components and yield potential is presented in Table 6.

Table 6. F Statistics for GCA, SCA, and Reciprocal Effects on Yield Components and Yield Potential

Source of Variation	df	NKRE	NKR	EWH	EWWH	KWE	HM	B1000	YP
GCA	4	28.73^{**}	8.63^{**}	25.85^{**}	26.46^{**}	15.46^{**}	19.69^{**}	24.76^{**}	10.89^{**}
SCA	10	1.26^{ns}	6.12^{**}	5.84^{**}	6.27^{**}	5.98^{**}	2.63^{*}	2.68^{*}	5.93^{**}
Reciprocal	10	1.68^{ns}	1.25^{ns}	0.36^{ns}	0.36^{ns}	0.32^{ns}	1.72^{ns}	0.72^{ns}	0.36^{ns}

Note: NKRE = number of kernel rows per ear; NKR = number of kernels per row; EWH = ear weight with husk; EWWH = ear weight without husk; KWE = kernel weight per ear; HM = harvest moisture content; B1000 = 1000-kernel weight; YP = yield potential. ns = not significant; * = significant at 5%; ** = significant at 1%.

In Table 6, GCA had highly significant effects on all eight yield components and yield potential-related traits presented. SCA was highly significant for kernels per row, ear weight with husk, ear weight without husk, kernel weight per ear, and yield potential; it was significant for harvest moisture content and 1000-kernel weight, but was not significant for kernel rows per ear. Both additive-related and non-additive-related combining-ability effects are therefore relevant to several yield traits.

Reciprocal effects were not significant for any yield component or for yield potential (Table 6). Thus, the two crossing directions did not show statistically detectable differences in these traits under this

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experiment. Practical seed-production considerations may guide crossing direction, while the significant reciprocal effect for ear length (Table 5) warrants attention.

The significant effects of both GCA and SCA on yield potential indicate that selection should not rely solely on parental performance or on a specific cross combination. Instead, maize hybrid development should integrate favorable parental GCA, positive SCA effects, and superior mean performance. This interpretation is consistent with previous studies emphasizing the combined importance of additive and non-additive genetic effects in hybrid maize breeding (Amzeri et al., 2025; Suyadi et al., 2021).

The GCA effects of the five inbred parents varied across the evaluated traits. The GCA estimates for vegetative traits, flowering time, harvest age, ear length, and ear diameter are presented in Table 7, whereas those for yield components and yield potential are presented in Table 8.

Table 7. General Combining Ability Values of Five Parents for Vegetative Component Traits, Anthesis and Silking Flowering Time, and Ear Length and Ear Diameter

Parents	PH	EH	SD	A50	S50	HA	EL	ED
Mz1	-6.62	-2.39	-0.39	-1.28	-1.22	-1.22	-1.15	-1.35
Mz2	3.59	2.51	0.20	-0.09	-0.19	-0.19	0.16	0.80
Mz3	-5.04	-0.70	-0.05	0.04	-0.09	-0.09	-0.08	-0.31
Mz4	5.34	0.07	0.08	0.98	0.97	0.97	0.59	0.84
Mz5	2.73	0.50	0.16	0.35	0.54	0.54	0.49	0.02

Note: PH = plant height; EH = ear height; SD = stem diameter; A50 = 50% anthesis; S50 = 50% silking; HA = harvest age; EL = ear length; ED = ear diameter. Positive or negative GCA values indicate the direction of parental contribution to each trait.

The GCA estimates presented in Table 7 indicate differences in the direction and magnitude of parental contributions to vegetative, flowering, maturity, and ear traits. Mz1 showed the most negative GCA effects for plant height (−6.62) and ear height (−2.39). GCA effects were highly significant for plant height but not significant for ear height. These findings indicate that Mz1 has a favorable combining ability for reducing plant height, whereas its negative GCA effect for ear height should be interpreted cautiously because the overall GCA effect was not statistically significant.

For flowering and harvest age, Mz1 showed negative GCA effects for 50% anthesis (−1.28), 50% silking (−1.22), and harvest age (−1.22), indicating its potential contribution to earlier reproductive development and maturity. In contrast, Mz4 showed the highest positive GCA effects for these traits. Because GCA effects for flowering and harvest age were highly significant, Mz1 may be considered a useful parental source when earlier maturity is a breeding objective.

For ear traits, Mz4 showed the highest positive GCA effects for ear length (0.59) and ear diameter (0.84), while Mz2 also showed a favorable positive effect for ear diameter (0.80). These results indicate that Mz4 and Mz2 contributed favorable additive genetic effects to ear morphology. The significant GCA effects for ear length and ear diameter support their potential use as parental lines for improving these traits. Previous studies have similarly emphasized the usefulness of GCA estimates for identifying maize parents with favorable contributions to agronomic and ear-related traits (Ali et al., 2025; Suyadi et al., 2021). The GCA effects for yield components and yield potential are presented in Table 8.

Table 8. General Combining Ability Values of Five Parents for Yield Components and Yield Potential

Parents	NKRE	NKR	EWH	EWWH	KWE	HM	B1000	YP
Mz1	0.53	-1.30	-30.24	-25.99	-13.66	-1.34	-30.80	-0.97
Mz2	0.44	0.98	11.44	11.07	9.58	-0.26	0.28	0.85
Mz3	0.06	-0.32	-6.94	-6.25	-2.13	0.33	-3.33	-0.24
Mz4	-0.59	0.18	18.03	13.55	4.34	0.33	22.95	0.32
Mz5	-0.44	0.46	7.71	7.62	1.87	0.94	10.90	0.03

Note: NKRE = number of kernel rows per ear; NKR = number of kernels per row; EWH = ear weight with husk; EWWH = ear weight without husk; KWE = kernel weight per ear; HM = harvest moisture content; B1000 = 1000-kernel weight; YP = yield potential. Positive or negative GCA values indicate the direction of parental contribution to each trait.

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The GCA effects presented in Table 8 indicate that Mz2 and Mz4 were the most favorable general combiners for several yield-related traits. Mz2 showed positive GCA effects for the number of kernels per row (0.98), ear weight without husk (11.07), kernel weight per ear (9.58), and yield potential (0.85). Mz4 showed positive effects for ear weight with husk (18.03), ear weight without husk (13.55), kernel weight per ear (4.34), 1000-kernel weight (22.95), and yield potential (0.32). These results indicate that Mz2 and Mz4 contributed favorable additive genetic effects to several important yield components and can be prioritized as parental lines in further hybrid development.

In contrast, Mz1 showed negative GCA effects for the number of kernels per row (−1.30), ear weight with husk (−30,24), ear weight without husk (−25.99), kernel weight per ear (−13.66), 1000-kernel weight (−30.80), and yield potential (−0.97). However, its negative GCA effect for harvest moisture content (−1.34), together with its negative effects for flowering and harvest age, suggests that Mz1 may be useful when earlier maturity and lower grain moisture at harvest are breeding objectives.

The positive GCA effects of Mz2 and Mz4 for yield potential are consistent with their favorable contributions to several yield components. This pattern demonstrates the importance of evaluating parental combining ability across multiple traits rather than relying on yield potential alone. Similar studies have shown that maize parental selection should integrate favorable GCA effects for yield components, maturity, and final yield performance (Amzeri et al., 2025; Suwarno et al., 2023; Suyadi et al., 2021).

The SCA effects varied among the specific F1 cross combinations evaluated in this study. The SCA estimates for vegetative traits, flowering time, harvest age, ear length, and ear diameter are presented in Table 9, whereas those for yield components and yield potential are presented in Table 10.

Table 9. Specific Combining Ability Values of F1 Hybrids for Vegetative Component Traits, Anthesis and Silking Flowering Time, And Ear Length and Ear Diameter

Hybrid Code	PH	EH	SD	A50	S50	HA	EL	ED
HUA1	-7.99	0.21	0.53	0.14	-0.12	-0.12	1.11	-0.33
HUA2	-10.49	-0.73	-0.14	0.20	0.30	0.30	-0.07	-0.47
HUA3	2.51	7.99	-0.33	-0.59	-0.87	-0.87	0.06	0.84
HUA4	25.48	4.54	0.17	-0.12	0.35	0.35	0.15	1.14
HUA5	7.25	2.10	0.78	0.72	0.85	0.85	0.38	-0.70
HUA6	-2.16	-2.35	-0.07	0.16	0.36	0.36	0.22	1.81
HUA7	-3.52	0.02	-0.47	0.47	0.22	0.22	-0.04	0.63
HUA8	5.64	-0.03	0.70	0.75	0.50	0.50	1.08	1.17
HUA9	5.56	4.89	0.67	-1.07	-1.07	-1.07	0.40	0.69
HUA10	-14.27	-5.12	0.02	0.45	0.30	0.30	-0.57	-0.72
HUA11	-14.27	-5.12	0.02	0.45	0.30	0.30	-0.57	-0.72
HUA12	5.56	4.89	0.67	-1.07	-1.07	-1.07	0.40	0.69
HUA13	-3.52	0.02	-0.47	0.47	0.22	0.22	-0.04	0.63
HUA14	25.48	4.54	0.17	-0.12	0.35	0.35	0.15	1.14
HUA15	5.64	-0.03	0.70	0.75	0.50	0.50	1.08	1.17
HUA16	-2.16	-2.35	-0.07	0.16	0.36	0.36	0.22	1.81
HUA17	2.51	7.99	-0.33	-0.59	-0.87	-0.87	0.06	0.84
HUA18	7.25	2.10	0.78	0.72	0.85	0.85	0.38	-0.70
HUA19	-10.49	-0.73	-0.14	0.20	0.30	0.30	-0.07	-0.47
HUA20	-7.99	0.21	0.53	0.14	-0.12	-0.12	1.11	-0.33

Note: PH = plant height; EH = ear height; SD = stem diameter; A50 = 50% anthesis; S50 = 50% silking; HA = harvest age; EL = ear length; ED = ear diameter. Positive or negative SCA values indicate the direction of specific cross contribution to each trait.

The SCA estimates presented in Table 9 indicate differences in the direction and magnitude of specific cross effects for vegetative, flowering, maturity, and ear traits. However, SCA effects for plant height, ear height, stem diameter, flowering time, and harvest age were not statistically significant.

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Therefore, the estimates for these traits should be interpreted primarily as indications of the direction of specific cross effects rather than as evidence of statistically confirmed superiority.

HUA9 and HUA12, representing the reciprocal Mz5 × Mz3 and Mz3 × Mz5 combinations, showed the most negative SCA effects for 50% anthesis, 50% silking, and harvest age, each at −1.07. These estimates suggest a tendency toward earlier flowering and maturity, although the overall SCA effects for these traits were not significant.

In contrast, SCA effects were highly significant for ear length and ear diameter. HUA8 and HUA15, representing the Mz4 × Mz3 combination, showed the highest positive SCA effect for ear length (1.08). HUA6 and HUA16, representing the Mz4 × Mz2 combination, showed the highest positive SCA effect for ear diameter (1.81). These findings indicate favorable specific parental compatibility for ear development in the respective cross combinations. Previous studies have similarly shown that SCA information is useful for identifying maize crosses with favorable non-additive contributions to ear-related traits (Ali et al., 2025; Suyadi et al., 2021). The corresponding SCA estimates for yield components and yield potential are presented in Table 10.

Table 10. Specific Combining Ability Values of F1 Hybrids for Yield Components and Yield Potential

Hybrid Code	NKRE	NKR	EWH	EWWH	KWE	HM	B1000	YP
HUA1	-0.25	1.82	9.17	5.30	4.65	0.36	-0.11	0.33
HUA2	-0.13	-0.76	-10.48	-8.28	-4.83	-0.11	-8.82	-0.36
HUA3	-0.10	0.49	8.25	9.17	6.49	-0.39	7.19	0.61
HUA4	-0.02	0.39	11.98	10.04	7.36	-0.47	14.31	0.67
HUA5	0.17	-0.07	-5.75	-4.46	-3.02	0.27	-9.68	-0.31
HUA6	0.16	1.41	26.01	24.23	16.88	-1.30	18.52	1.61
HUA7	0.00	0.38	9.02	8.95	4.17	0.12	8.37	0.40
HUA8	-0.06	1.43	20.70	15.65	9.76	-0.30	13.36	0.85
HUA9	-0.22	1.50	16.35	14.13	9.71	-0.70	11.02	0.90
HUA10	0.36	-0.57	-22.10	-17.36	-11.27	0.64	-25.83	-1.05
HUA11	0.36	-0.57	-22.10	-17.36	-11.27	0.64	-25.83	-1.05
HUA12	-0.22	1.50	16.35	14.13	9.71	-0.70	11.02	0.90
HUA13	0.00	0.38	9.02	8.95	4.17	0.12	8.37	0.40
HUA14	-0.02	0.39	11.98	10.04	7.36	-0.47	14.31	0.67
HUA15	-0.06	1.43	20.70	15.65	9.76	-0.30	13.36	0.85
HUA16	0.16	1.41	26.01	24.23	16.88	-1.30	18.52	1.61
HUA17	-0.10	0.49	8.25	9.17	6.49	-0.39	7.19	0.61
HUA18	0.17	-0.07	-5.75	-4.46	-3.02	0.27	-9.68	-0.31
HUA19	-0.13	-0.76	-10.48	-8.28	-4.83	-0.11	-8.82	-0.36
HUA20	-0.25	1.82	9.17	5.30	4.65	0.36	-0.11	0.33

Note: NKRE = number of kernel rows per ear; NKR = number of kernels per row; EWH = ear weight with husk; EWWH = ear weight without husk; KWE = kernel weight per ear; HM = harvest moisture content; B1000 = 1000-kernel weight; YP = yield potential. Positive or negative SCA values indicate the direction of specific cross contribution to each trait.

The SCA estimates presented in Table 10 show that the Mz2 × Mz4 combination, represented by HUA6 and HUA16, had the most favorable specific cross effects for several yield-related traits. Both hybrids showed the highest positive SCA effects for yield potential (1.61), ear weight without husk (24.23), kernel weight per ear (16.88), and 1000-kernel weight (18.52), together with a favorable negative effect for harvest moisture content (−1.30). These results indicate favorable non-additive contributions of the Mz2 × Mz4 parental combination to kernel productivity, yield potential, and lower harvest moisture.

HUA9 and HUA12, representing the Mz5 × Mz3 combination, also showed positive SCA effects for yield potential (0.90), followed by HUA8 and HUA15 from the Mz4 × Mz3 combination (0.85). In contrast,

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HUA10 and HUA11, representing the Mz5 × Mz4 combination, showed the most negative SCA effects for yield potential (−1.05), ear weight without husk (−17.10), kernel weight per ear (−11.27), and 1000-kernel weight (−25.83). These results demonstrate that favorable GCA of an individual parent does not necessarily result in favorable SCA in every hybrid combination. Therefore, both parental GCA and specific cross performance should be considered in hybrid selection. Similar conclusions have been reported in maize breeding studies emphasizing the complementary use of GCA, SCA, and mean hybrid performance (Amzeri et al., 2025; Oktakia et al., 2025; Suyadi et al., 2021).

The identical SCA estimates observed between reciprocal pairs, such as HUA6 and HUA16, are expected because SCA represents the effect of a parental combination regardless of crossing direction; this does not imply that reciprocal effects are absent for all traits. The analysis detected a significant reciprocal effect for ear length, but not for yield potential or the other 14 traits.

The Mz2 × Mz4 combination was the most promising because it combined favorable parental GCA, high positive SCA effects, and high mean yield performance. Nevertheless, because the experiment was conducted in a single environment, the performance of HUA6 and HUA16 should be validated through further yield testing and multi-location evaluation.

Heterosis, Heterobeltiosis, Standard Heterosis, and Hybrid Candidate Selection

Heterosis, heterobeltiosis, and standard heterosis were calculated to evaluate hybrid performance relative to the mid-parent, better parent, and P32 check hybrid, respectively. The estimates for yield potential are presented in Table 11.

Table 11. Heterosis, Heterobeltiosis, and Standard Heterosis of Maize Hybrids for Yield Potential

Hybrid Code	Crossing	F1 yield potential (t ha^{-1})	Heterosis (%)	Heterobeltiosis (%)	Standard Heterosis vs P32 (%)
HUA1	Mz2 × Mz1	11.55	25.55	8.62	-3.16
HUA2	Mz3 × Mz1	9.41	9.71	0.16	-21.05
HUA3	Mz4 × Mz1	11.06	27.53	15.40	-7.21
HUA4	Mz5 × Mz1	10.83	21.20	7.15	-9.14
HUA5	Mz3 × Mz2	10.96	9.45	3.10	-8.08
HUA6	Mz4 × Mz2	13.73	35.86	29.19	15.18
HUA7	Mz5 × Mz2	12.10	16.74	13.89	1.51
HUA8	Mz4 × Mz3	12.25	29.04	27.78	2.74
HUA9	Mz5 × Mz3	12.12	24.30	19.93	1.68
HUA10	Mz5 × Mz4	9.93	0.82	-1.79	-16.75
HUA11	Mz4 × Mz5	10.60	7.60	4.81	-11.13
HUA12	Mz3 × Mz5	11.19	14.70	10.68	-6.18
HUA13	Mz2 × Mz5	12.39	19.49	16.57	3.94
HUA14	Mz1 × Mz5	10.56	18.18	4.47	-11.43
HUA15	Mz3 × Mz4	11.53	21.47	20.28	-3.27
HUA16	Mz2 × Mz4	13.75	36.03	29.35	15.32
HUA17	Mz1 × Mz4	10.78	24.27	12.46	-9.62
HUA18	Mz2 × Mz3	11.57	15.58	8.89	-2.94
HUA19	Mz1 × Mz3	9.37	9.18	-0.32	-21.41
HUA20	Mz1 × Mz2	10.81	17.51	1.66	-9.37

Note: F1 = first-generation hybrid; mid-parent = mean yield potential of the two parental inbred lines; better parent = parental inbred line with the higher yield potential; P32 = commercial check hybrid. Heterosis, heterobeltiosis, and standard heterosis were calculated relative to the mid-parent, better parent, and P32, respectively. Positive values indicate higher hybrid yield potential than the corresponding reference, whereas negative values indicate lower yield potential. All percentages are based on yield potential.

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The values in Table 11 show positive heterosis and heterobeltiosis for yield potential in many hybrid combinations. HUA16 and HUA6 had the highest heterosis values, 36.03% and 35.86%, and heterobeltiosis values, 29.35% and 29.19%, respectively, indicating higher estimated yield potential than both the parental mean and the better parent.

HUA16 and HUA6 also showed positive standard heterosis relative to P32 of 15.32% and 15.18%, respectively. These differences are numerical: both hybrids had higher estimated yield potential than P32, but neither differed significantly from P32 according to Tukey's HSD at 5%. Their selection for further testing is supported by mean yield, parental combining ability, cross-specific effects, and heterosis, rather than a claim of statistically superior yield over the check (Amzeri et al., 2025; Oktakia et al., 2025).

In addition to HUA16 and HUA6, four hybrids showed positive standard heterosis relative to P32: HUA13 (3.94%), HUA8 (2.74%), HUA9 (1.68%), and HUA7 (1.51%). Their yield potentials were 12.39, 12.25, 12.12, and 12.10 t ha^{-1}, respectively. Although their values were lower than those of HUA16 and HUA6, these hybrids may be considered supporting candidates for further evaluation because their mean yield performance numerically exceeded that of P32.

Based on the combined evidence from mean yield performance, GCA, SCA, heterosis, heterobeltiosis, and standard heterosis, HUA16 and HUA6 can be prioritized as the primary hybrid candidates, followed by HUA13, HUA8, HUA9, and HUA7 as supporting candidates. However, the present results were obtained from a single location and growing season and therefore cannot be used to conclude yield stability or adaptability. The selected hybrids should be evaluated through further yield trials and multi-location testing to determine their performance across environments. This recommendation is consistent with Wicaksana et al. (2022), who emphasized the importance of genotype × environment interaction, stability, and adaptability in selecting high-yielding maize hybrids.

CONCLUSION

Based on the analysis, genotype effects were significant or highly significant for 14 of 16 traits, whereas ear height and stem diameter were not significant. Yield potential had high broad-sense heritability (77.79%) based on genotype means. HUA16 and HUA6 had the highest estimated yield potentials, 13.75 and 13.73 t ha^{-1}, respectively, but were not significantly different from P32 according to Tukey's HSD at 5%. GCA was highly significant for 14 traits and SCA was significant or highly significant for nine traits. Mz2 showed the highest GCA for yield potential (0.85), and the Mz2 × Mz4 combination had the highest SCA for yield potential (1.61). Reciprocal effects were significant only for ear length, not for yield potential. HUA16 and HUA6 displayed heterosis of 36.03% and 35.86%, heterobeltiosis of 29.35% and 29.19%, and numerically positive standard heterosis relative to P32 of 15.32% and 15.18%, respectively. These two hybrids are recommended as priorities for further yield and multi-location evaluation. Additional testing is needed before drawing conclusions on yield stability or broad adaptability.

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