

RESEARCH ARTICLE

# Comparative Evaluation of Three Methods for Heterotic Grouping in Yellow Maize

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## ABSTRACT

Evaluation and classification of inbred lines are crucial for accelerating the development of high-yielding, superior maize hybrids. This study aimed to assess combining ability effects of diverse maize inbred lines using the line × tester mating design, and to compare the effectiveness of three methods, HSCA, HSGCA, and HGCAMT, for classifying inbred lines into heterotic groups. The plant materials included two distinct sets of yellow maize inbred lines, each set comprising 21 diverse inbred lines crossed with two testers to generate 42 hybrids. The resulting hybrids in each set and two checks, i.e., SC.168 and Corteva SC.3444, were evaluated at Sakha and Gemmiza Agricultural Research Stations during the 2024 growing season using a randomized complete block design with three replications. The results indicated that the HSGCA method provided the highest breeding efficiency and identified the superior inter-group hybrids, followed by HSCA and HGCAMT. Four inbred lines, Inb-02, Inb-07, Inb-08 and Inb-14 from set-1 and six inbred lines, Inb-28, Inb-29, Inb-32, Inb-33, Inb-37 and Inb-41 from set-2 had desirable GCA effects for high grain yield. Furthermore, five hybrids, H-13, H-14, H-15, H-63 and H-73, significantly outyielded two checks. Hence, they were identified as promising hybrids in the present study and recommended for further multi-environment evaluation.

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## INTRODUCTION

Maize (*Zea mays* L.) is one of the world's most important cereal crops, serving as a staple food, animal feed, and industrial raw material, including biofuels across diverse agro-ecological zones (Bankole *et al.*, 2023). In Egypt, maize is an indispensable crop that plays a crucial role in national food security and livestock production. Its high nutritional value enhances its importance for human consumption and a range of industrial applications, including the production of corn oil, fructose, and starch (Abd El Fatah *et al.*, 2015). However, Egypt continues to

face a gap between maize production and rising consumption, as production is sufficient to cover only about 50% of consumption. Hence, the total area and grain yield/ unit should be increased (Mosa *et al.*, 2022, and Ismail *et al.*, 2024a). Egyptian maize yields are often constrained by limited arable land, suboptimal hybrid combinations, environmental stresses such as drought and heat, and water scarcity. Addressing these challenges requires developing high-yielding, stress-resilient hybrids that perform well under these conditions (Ismail *et al.*, 2023).

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The line  $\times$  tester mating technique is robust and widely adopted in maize breeding, enabling the assessment of general and specific combining abilities among inbred lines and testers. Consequently, it facilitates the identification of superior parental inbreds for the development of high-yielding hybrids (Kempthorne, 1957; Ismail *et al.*, 2020a; Ismail *et al.*, 2020b; Patil *et al.*, 2020; Job and Igyuve, 2022; and Subba *et al.*, 2022). Classification of inbreds into heterotic groups is essential for exploiting hybrid vigour. Several methods have been developed to assign inbred lines to heterotic groups, including those based on specific combining ability (HSCA), a combination of general and specific combining ability (HSGCA), and multivariate approaches such as heterotic grouping based on general combining ability of multiple traits (HGCAMT) (Vasal *et al.*, 1992; Fan *et al.*, 2009; Badu-Apraku *et al.*, 2013; Ismail *et al.*, 2022; Ismail *et al.*, 2023; and Mosa *et al.*, 2024). By categorizing inbred lines into heterotic-defined groups, breeders can systematically form and evaluate hybrids. Thereby saving time and resources rather than the random crossing and testing (Labroo *et al.*, 2021). The breeding efficiency results highlight the importance of selecting appropriate methods to make heterotic groups and parental combinations to achieve specific breeding goals (Fan *et al.*, 2009, Amegbor *et al.*, 2017 and Mosa *et al.*, 2025). Although these methods are widely applied, comparative assessments of these methods under Egyptian conditions are limited. Therefore, the objectives of this study were to evaluate the combining ability effects of diverse maize inbred lines using the line  $\times$  tester mating design, and to compare the effectiveness of three heterotic grouping methods, HSCA, HSGCA, and HGCAMT, in classifying inbred lines and predicting superior hybrid combinations under Egyptian environmental conditions.

## MATERIALS AND METHODS

### Plant materials:

The plant materials included two distinct sets of yellow maize inbred lines, each set comprising 21 diverse inbred lines (Table 1). Two testers, i.e., inbred lines GM-6052 ( $T_1$ ) and GZ-658 ( $T_2$ ), were used to create hybrid combinations with the two sets of inbred lines, using the line  $\times$  tester model according to Kempthorne (1957) during the 2023 season. The inbred lines and testers were developed by the Maize Research Department at Gemmiza Agricultural

Research Station, in the Agricultural Research Center (ARC), Egypt. Two check hybrids, namely single cross (SC 168) developed by ARC and pioneer single cross (SC 3444) from Corteva Agriscience, served as commercial standards.

### Experimental design and field evaluation:

The 42 formed hybrids from each set, along with the two checks, were evaluated at two locations, Gemmiza and Sakha Agricultural Research Stations, during the 2024 growing season. The experiment for each set was laid out in a randomized complete block design (RCBD) with three replications per location. The trial plot was a single row measuring 6.0 m long, with inter- and intra-row spacing of 0.80 m and 0.25 m, respectively. Initial seeding was two kernels per hill, and later thinned to one plant per hill at the first irrigation. Standard agronomic practices were employed at both locations to ensure a good crop standing.

### Data Collection

Data were recorded on number of days to 50% silking DSK (day), plant height PHT (cm), ear height EHT (cm), and grain yield (GY) per plot adjusted at 15.5% grain moisture and converted to (ard./fed.), one ardab (ard.) = 140 kilograms and one feddan (fed) = 4200 m<sup>2</sup>.

### Data analysis

The combined analysis of collected data was performed across two locations after a Bartlett (1937) homogeneity test using SAS software (SAS Institute Inc., 2008) according to Snedecor and Cochran (1989). General and specific combining abilities were estimated using the line  $\times$  tester analysis mating design proposed by Kempthorne (1957).

### Heterotic group:

Three methods were employed to make heterotic groups. The first method for forming a heterotic group using specific combining ability (HSCA) effects was described by Vassal *et al.*, (1992). The second method, according to Fan *et al.* (2009), using specific and general combining ability (HSGCA). Meanwhile, the third method to make heterotic groups was based on the general combining ability of multiple traits (HGCAMT), as described by Badu-Apraku *et al.*, (2013).

### Breeding efficiency:

Two methods were employed to evaluate breeding efficiency. The first method, as proposed by

**Table 1. List of mane of maize inbred lines, and their codes.**

Set-I		Set-II	
Inbred line	Code	Inbred line	Code
GM-72-4	Inb. 01	GM-27-2	Inb. 22
GM-72-20	Inb. 02	GM-27-3	Inb. 23
GM-72-23	Inb. 03	GM-27-4	Inb. 24
GM-72-24	Inb. 04	GM-27-10	Inb. 25
GM-72-25	Inb. 05	GM-27-12	Inb. 26
GM-72-26	Inb. 06	GM-27-13	Inb. 27
GM-72-27	Inb. 07	GM-27-17	Inb. 28
GM-72-28	Inb. 08	GM-27-19	Inb. 29
GM-72-29	Inb. 09	GM-27-21	Inb. 30
GM-72-39	Inb. 10	GM-27-22	Inb. 31
GM-72-40	Inb. 11	GM-27-23	Inb. 32
GM-72-41A	Inb. 12	GM-27-24	Inb. 33
GM-72-41B	Inb. 13	GM-27-25	Inb. 34
GM-72-42	Inb. 14	GM-27-26	Inb. 35
GM-72-45	Inb. 15	GM-27-27	Inb. 36
GM-72-46	Inb. 16	GM-72-22	Inb. 37
GM-72-49	Inb. 17	GM-72-60	Inb. 38
GM-72-50	Inb. 18	GM-72-65	Inb. 39
GM-72-51	Inb. 19	GM-72-66	Inb. 40
GM-72-52	Inb. 20	GM-72-69	Inb. 41
GM-72-59	Inb. 21	GM-72-70	Inb. 42

Fan et al. (2009), defined breeding efficiency (grouping efficiency) using the following formula:

$$\text{Breeding Efficiency (\%)} = \frac{\text{HY Inter HG}}{\text{TN Inter HG}} \times 100$$

HY Inter HG = number of high-yielding inter-heterotic group hybrids;TN Inter HG = total number of inter-heterotic group hybrids.

The second method was adapted from the breeding efficiency proposed by Fan et al. (2009) and further modified by Badu-Apraku et al. (2016). According to Annor et al., (2020), using the following formula:

$$\text{Breeding Efficiency (\%)} = \frac{\frac{\text{HY Inter HG}}{\text{TN Inter HG}} \times 100 + \frac{\text{LY Intra HG}}{\text{TN Intra HG}} \times 100}{2}$$

Where: HY Inter HG = number of high-yielding inter-heterotic group hybrids;

TN Inter HG = total number of inter-heterotic group hybrids.

LY Intra HG = number of low yielding intra-heterotic group hybrids.TN Intra HG = total number of intra-heterotic group hybrids.

## RESULTS AND DISCUSSION

### Analysis of variance:

The combined ANOVA of the hybrids for four traits across the two locations (Table 2) revealed highly significant mean squares (MS) of locations (Loc) for all study traits in two sets, except for DSK in Set 2, meaning that the environmental influence on the expression of these traits underscores the need for a multi-environment assessment of the hybrids. This finding is are in agreement with those reported by Mutimaamba et al., (2020), Habiba et al., (2022), Ismail et al., (2023), Ribeiro et al., (2023), Abd-Elaziz et al., (2024); and Bankole and Aboderin, (2024). The genotypes (Gen) and their partition hybrids (H) MS were highly significant for all measured traits, indicating that differences between genotypes and

between hybrids were observed in both sets. These results buttressed the findings of Oyetunde *et al.*, (2020), Adewale *et al.*, (2023), Ismail *et al.* (2020b) and Nivethitha *et al.*, (2023). The checks (ch.) MS was highly significant for ear height in both sets, indicating that the two checks differed significantly in this respect. The hybrids vs. checks (H vs ch) MS was significant or highly significant for all measured traits in both sets, except for PHT and EHT in set 1, suggesting that the hybrid averages differed significantly from the check averages. The highly significant MS were detected in the interaction Gen x Loc and their partition H x Loc, for all traits except EHT in set-1, indicating that the expression of these traits would be inconsistent in varying test locations and highlights the importance of identifying high-yielding and stable hybrids across environments (Amegbor *et al.*, 2017). Conversely, the interaction Ch x Loc was insignificant for all traits in both sets, except for EHT in set I, indicating that checks are stable across the tested locations. The interaction of H vs Ch x Loc was significant or highly significant for grain yield in set-1 and set-2, respectively, and it was also highly significant for DSK in set-2, indicating that hybrid vs check was affected by locations.

#### **Combining ability analysis:**

Lines, testers, and line x tester MS were identified as highly significant for all the examined traits except tester for EHT in set 2 (Table 3), evincing the presence of variation between the inbreds and testers, also indicating that the inbred lines performed differently in their respective crosses depending on the type of testers used for these traits. Additionally, the results indicated that inbreds are diverged and could be classified into heterotic groups. These results are in harmony with the findings of Akinwale *et al.*, (2014), Badu-Apraku *et al.*, (2015), Ruswandi *et al.*, (2015), Ismail *et al.*, (2024a), and Tabu *et al.*, (2023). The significance of lines x Loc, testers x Loc, and lines x testers x Loc for most of the examined traits indicates that lines, testers, and their interaction fluctuated from one location to another. These results agree with the findings of Badu-Apraku *et al.*, (2013) and El-Gazzar *et al.*, (2013).

#### **Contributions of lines, testers, and Lines x Testers in total sum squares of hybrids:**

The line proportions of the total sum squares of hybrids were higher than the testers' proportions for all the studied traits in both sets, except PHT in set 1,

indicating that selecting lines with significant desirable GCA effects for these traits could be effective for improving them (Figure 1). Similar findings were reported by Efendi *et al.*, (2024). The proportions of line x testers were 35.45% and 44.76% for grain yield in sets 1 and 2, respectively, and 40.93% for DSK in set 1, highlighting the importance of heterosis for these traits. The dominance of GCA (GCA line + GCA tester) over the SCA (SCA line x tester) for all the studied traits implied that additive gene action was more important than non-additive gene action for all traits in both inbred sets, representing that GCA was the leading player accounting for the differences among the hybrids (Figure 2). These findings corroborated the results of (Dhasarathan *et al.*, 2015; Ismail *et al.*, 2023; Tabu *et al.*, 2023). Makumbi *et al.*, (2011) reported that inbred lines that exhibit positive GCA effects for grain yield and other traits are likely to transmit these desirable characteristics to their progeny, thereby rendering them valuable genetic resources in breeding programs.

#### **Mean Performance:**

For days to 50 % silking, all hybrids from both inbred line sets were significantly earlier than the two checks (65 days), except H-19, H-31, H-32, H-36, and H-62 (Table 4). Thus, they could be exploited to develop early-maturity hybrids. The hybrids H-12 and H-40 in set I showed significantly lower plant height (PHT) than the best check, SC 168. Similarly, in set 2, the hybrids; H-44, H-46, H-52, H-53, H-54, H-58, H-60, H-66, H-70, H-72, H-74 and H-80 were also shorter than the same check. In set I, none of the hybrids showed a significantly lower ear placement than the best check, SC 3444. Meanwhile, in set 2, seven hybrids, i.e., H-43, H-44, H-45, H-46, H-67, H-70, H-74, and H-75, recorded the lowest ear placement compared to the best check SC 3444 (146.17 cm). Ismail *et al.*, (2024b) reported that short-statured maize hybrids are advantageous for reducing lodging and enabling higher planting densities, whereas taller hybrids are better suited for silage production. For grain yield, three hybrids, H-13, H-14, and H-15 in set 1 and two hybrids, H-63 and H-73 in set 2, significantly outyielded the best check hybrid SC 3444. Thus, these hybrids would be advanced for multilocation yield trials before being promoted for commercialisation in the Egyptian market to improve food security.

**Table 2. Mean squares due to locations, hybrids, checks, and their interactions for examined traits in two sets.**

S.O.V	d.f	Set 1				Set 2			
		DSK	PHT	EHT	GY	DSK	PHT	EHT	GY
Locations (Loc)	1	258.03**	110045.83**	21546.31**	3301.35**	4.64	119637.88**	40950.55**	3031.74**
Rep/Loc	4	1.17	774.24	302.44	38.94	6.29	816.06	292.98	39.49
Genotypes(Gen)	43	8.64**	835.72**	434.33**	69.76**	10.05**	857.19**	821.39**	125.80**
Hybrids (H)	41	7.98**	873.88**	430.70**	72.15**	8.55**	880.39**	814.38**	123.94**
Checks (Ch)	1	2.08	40.33	867.00**	9.41	0.75	176.33	1140.75**	10.68
H vs Ch	1	42.08**	66.68	150.36	32.01*	80.73**	587.02*	789.41**	317.32**
Gen × Loc	43	2.78**	301.34**	146.39	44.94**	2.79**	217.04**	142.51**	48.48**
H × Loc	41	2.88**	308.09**	132.62	46.18**	2.58**	225.12**	143.19**	48.98**
Ch × Loc	1	0.75	1.33	800.33**	2.44	0.08	21.33	200.08	20.27
H vs Ch vs Loc	1	0.72	324.85	57.17	36.57*	13.84**	81.45	56.97	56.39**
Error	172	0.98	121.24	106.17	7.47	1.21	102.41	78.79	7.82
CV%		1.57	3.81	6.16	9.46	1.76	3.80	6.00	10.74

\* Significant at  $p < 0.05$ , \*\* significant at  $p < 0.01$

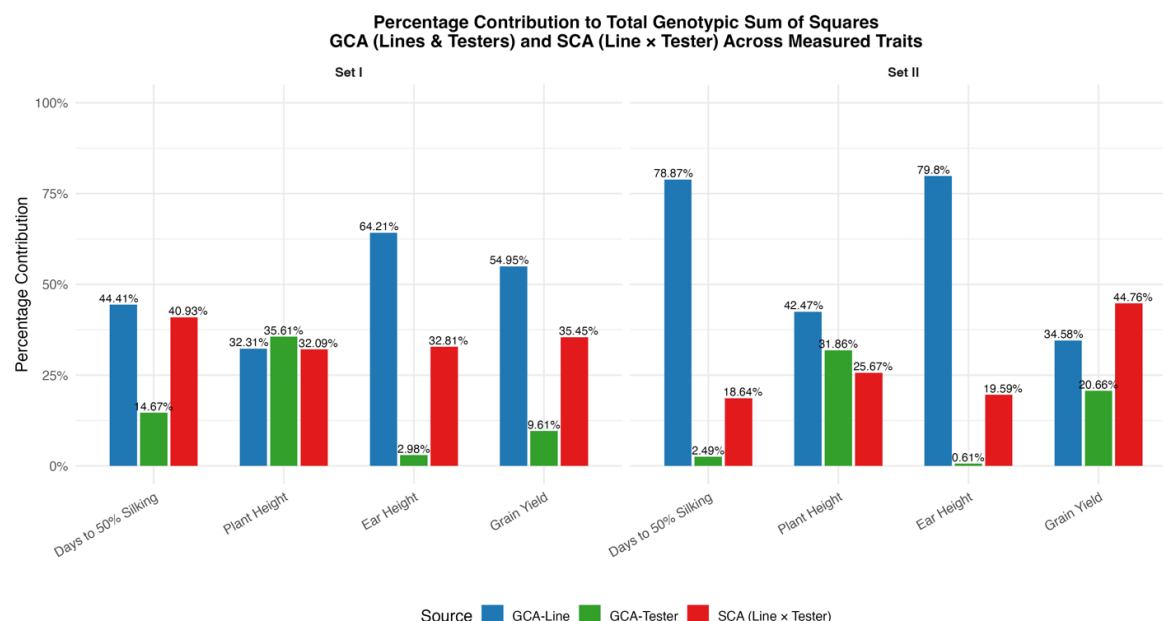
DSK= Days to 50% silking (day), PHT= Plant height (cm), EHT= Ear height (cm), GY= Grain yield (ard/fed).

**Table 3. Mean squares due to lines, testers, lines × testers, and their interactions with locations (Loc) for four traits in two sets.**

S.O.V	d.f	Set 1				Set 2			
		DSK	PHT	EHT	GY	DSK	PHT	EHT	GY
Lines	20	7.27**	644.15**	599.12**	87.16**	14.29**	838.91**	1332.26**	87.86**
Testers	1	48.02**	12069.59**	472.32**	259.04**	7.68**	10699.06**	204.48	1049.72**
Lines × Testers	20	6.70**	543.82**	260.20**	47.79**	2.87**	430.94**	326.99**	113.73**
Lines × Loc	20	3.98**	246.10**	178.79	44.02**	4.13**	222.26**	136.67*	65.63**
Testers × Loc	1	0.40	3811.11**	8.04	152.77**	1.29	825.14**	246.04	89.35**
Lines × Testers × Loc	20	1.90*	194.93	92.68	43.02**	1.10	197.98*	144.56**	30.31**
Error	164	1.01	122.97	109.90	7.61	1.23	103.38	80.25	7.89

\* Significant at  $p < 0.05$ , \*\* significant at  $p < 0.01$

DSK= Days to 50% silking (day), PHT= Plant height (cm), EHT= Ear height (cm), GY = Grain yield (ard/fed).



**Figure 1. Percentage contribution of lines and testers and lines × testers to the total sum squares of hybrids for measured traits in two maize inbred sets.**

### General combining ability:

Significant negative GCA effects are desired for DSK, PHT, and EHT traits. At the same time, significant positive GCA values are preferred for GY. Inbred lines with desirable GCA effects could serve as donor parents to improve the traits they confer. In this regard, the tester GM.6052 ( $T_1$ ) was identified as a good combiner for DSK and GY in set 1 (Table 5). Whereas, the tester GZ.658 ( $T_2$ ) was a good combiner for PHT in set-1. The inbred lines Inb-01, Inb-03, Inb-04, Inb-05, Inb-06, Inb-12 in Set-1, and Inb-22, Inb-23, Inb-24, Inb-40, and Inb-42 in Set-2 possessed significant negative GCA effects for DSK, indicating their potential to transmit earliness alleles to their progenies. These inbreds could be utilized as donor parents in breeding programs targeting early-maturing maize hybrids. Short-stature plants are preferred to decrease lodging and increase plant densities. Significant negative GCA effects for PHT recorded by Inb-05, Inb-06, Inb-13, Inb-18, Inb-19 in set-1 and Inb-22, Inb-23, Inb-26, Inb-27, Inb-29, Inb-30, and Inb-40 in set-2. Lower ear position is preferred to reduce lodging, Inb-03, Inb-04, Inb-05, Inb-09 in set-1 and Inb-22, Inb-23, Inb-24, Inb-29, Inb-30 Inb-34, and Inb-37 in set-2 demonstrated significant negative GCA effects for EHT. Positive and significant GCA effects for yield were recorded by Inb-02, Inb-07, Inb-08, Inb-14 in set-1 and Inb-28, Inb-29, Inb-32, Inb-33, Inb-37, and Inb-41 in set-2. These inbred lines are

candidates for the development of high-yielding maize hybrids. Notably, inbred lines exhibiting desirable GCA effects for the respective traits could be used in hybrid development programs, employed for inbred line recycling, or used as testers to assess the combining ability of newly developed inbreds (Akinwale *et al.*, 2014; Ertiro *et al.*, 2017; Adewale *et al.*, 2023).

### Specific combining ability:

The significance of SCA effects refers to the non-additive genetic variance (dominance and epistasis) that contributes to trait expression in hybrid combinations. Early flowering is a desirable trait, as it enables the plant to escape drought stress and to cultivate multiple crops within a year (Shavrukov *et al.*, 2017; Ismail *et al.*, 2024a).

Significant and adverse SCA effects for DSK were observed in H-06, H-07, H-20, H-23, H-35, H-38 in set-1 and H-70, and H-80 in set-2, indicating their potential for an early-flowering breeding program (Table 6). The hybrids H-05, H-12, H-20, and H-21 in set-1, and H-67, H-70, H-74, and H-75 in set-2 showed adverse SCA effects for PHT, suggesting their potential in a high-density breeding program. Ear height is associated with lodging susceptibility. The desirable SCA effects for EHT were determined by the hybrids H-20, H-21 in set-1, and H-67, H-70, H-74, and H-75 in set-2. Lower ear height is preferred as it decreases lodging. These



**Table 4. Mean performance of 84 maize hybrids for four traits in two sets across two locations.**

Set- 1						Set- 2					
Code	Hybrid	DSK	PHT	EHT	GY	Code	Hybrid	DSK	PHT	EHT	GY
H-01	Inb. 01 × T-1	62	293.17	160.67	27.14	H-43	Inb. 22 × T-1	59	261.83	125.83	22.92
H-02	Inb. 01 × T-2	62	273.83	165.17	28.18	H-44	Inb. 22 × T-2	60	247.17	117.83	21.10
H-03	Inb. 02 × T-1	62	302.00	158.33	33.21	H-45	Inb. 23 × T-1	61	268.33	133.33	25.26
H-04	Inb. 02 × T-2	63	285.50	164.83	31.25	H-46	Inb. 23 × T-2	62	249.00	135.00	28.10
H-05	Inb. 03 × T-1	63	283.00	156.50	31.75	H-47	Inb. 24 × T-1	62	269.00	140.67	29.86
H-06	Inb. 03 × T-2	62	292.33	164.83	26.22	H-48	Inb. 24 × T-2	61	265.67	142.50	22.14
H-07	Inb. 04 × T-1	61	292.83	161.67	26.38	H-49	Inb. 25 × T-1	62	273.50	153.50	25.67
H-08	Inb. 04 × T-2	64	283.33	160.17	25.48	H-50	Inb. 25 × T-2	63	267.83	162.67	22.02
H-09	Inb. 05 × T-1	61	284.17	154.00	25.87	H-51	Inb. 26 × T-1	62	274.17	151.83	29.38
H-10	Inb. 05 × T-2	63	278.17	151.50	26.66	H-52	Inb. 26 × T-2	63	246.00	142.33	16.81
H-11	Inb. 06 × T-1	62	294.17	171.67	30.23	H-53	Inb. 27 × T-1	64	256.17	154.00	24.06
H-12	Inb. 06 × T-2	62	260.33	153.00	27.87	H-54	Inb. 27 × T-2	64	254.00	152.17	22.66
H-13	Inb. 07 × T-1	63	306.83	176.00	35.13	H-55	Inb. 28 × T-1	62	284.83	163.83	33.74
H-14	Inb. 07 × T-2	63	293.17	173.67	36.95	H-56	Inb. 28 × T-2	62	264.50	152.33	24.33
H-15	Inb. 08 × T-1	64	301.83	172.33	34.53	H-57	Inb. 29 × T-1	62	260.33	142.67	30.66
H-16	Inb. 08 × T-2	64	283.83	162.50	29.78	H-58	Inb. 29 × T-2	63	251.00	138.50	24.68
H-17	Inb. 09 × T-1	62	294.17	164.33	33.72	H-59	Inb. 30 × T-1	61	267.00	142.33	31.07
H-18	Inb. 09 × T-2	64	279.50	156.50	26.79	H-60	Inb. 30 × T-2	63	253.17	137.50	17.78
H-19	Inb. 10 × T-1	66	320.67	188.50	30.89	H-61	Inb. 31 × T-1	64	279.33	173.50	29.11
H-20	Inb. 10 × T-2	63	277.83	163.67	23.20	H-62	Inb. 31 × T-2	65	266.17	172.67	24.48
H-21	Inb. 11 × T-1	62	290.50	170.00	28.43	H-63	Inb. 32 × T-1	62	296.67	157.67	36.27
H-22	Inb. 11 × T-2	63	309.67	185.67	32.03	H-64	Inb. 32 × T-2	64	272.33	157.67	27.02
H-23	Inb. 12 × T-1	61	289.83	161.83	28.36	H-65	Inb. 33 × T-1	63	278.83	152.00	27.63
H-24	Inb. 12 × T-2	64	286.67	168.50	30.15	H-66	Inb. 33 × T-2	63	255.67	148.50	29.20
H-25	Inb. 13 × T-1	63	289.17	161.83	25.95	H-67	Inb. 34 × T-1	62	265.00	131.00	24.46
H-26	Inb. 13 × T-2	64	273.50	161.83	27.99	H-68	Inb. 34 × T-2	62	269.17	151.67	20.07
H-27	Inb. 14 × T-1	64	308.50	177.50	32.33	H-69	Inb. 35 × T-1	64	278.00	153.83	26.81
H-28	Inb. 14 × T-2	63	287.83	173.33	30.57	H-70	Inb. 35 × T-2	62	245.33	134.33	18.93
H-29	Inb. 15 × T-1	62	292.33	178.00	26.84	H-71	Inb. 36 × T-1	64	266.83	150.67	25.51
H-30	Inb. 15 × T-2	64	285.33	175.67	21.33	H-72	Inb. 36 × T-2	64	255.00	148.17	23.43
H-31	Inb. 16 × T-1	65	295.33	171.67	28.51	H-73	Inb. 37 × T-1	62	288.67	152.50	36.36
H-32	Inb. 16 × T-2	65	280.50	172.17	25.48	H-74	Inb. 37 × T-2	62	249.50	129.67	20.49
H-33	Inb. 17 × T-1	63	307.33	182.67	32.21	H-75	Inb. 38 × T-1	63	266.33	133.83	25.22
H-34	Inb. 17 × T-2	64	286.83	170.50	24.47	H-76	Inb. 38 × T-2	64	274.33	153.33	25.75
H-35	Inb. 18 × T-1	61	290.00	167.17	29.02	H-77	Inb. 39 × T-1	62	275.67	153.17	29.61
H-36	Inb. 18 × T-2	65	274.17	163.50	23.60	H-78	Inb. 39 × T-2	63	268.00	150.00	25.15
H-37	Inb. 19 × T-1	64	277.17	170.33	26.24	H-79	Inb. 40 × T-1	63	258.50	147.33	21.96
H-38	Inb. 19 × T-2	63	276.00	174.17	27.86	H-80	Inb. 40 × T-2	61	254.17	143.67	23.04
H-39	Inb. 20 × T-1	63	297.50	170.67	33.00	H-81	Inb. 41 × T-1	63	272.00	152.00	24.90
H-40	Inb. 20 × T-2	63	270.33	159.33	26.13	H-82	Inb. 41 × T-2	63	269.83	160.17	33.89
H-41	Inb. 21 × T-1	63	302.00	169.67	26.86	H-83	Inb. 42 × T-1	62	285.50	153.33	24.37
H-42	Inb. 21 × T-2	64	283.17	167.33	32.07	H-84	Inb. 42 × T-2	61	275.00	150.33	28.06
Check SC 168		65	284.67	172.33	29.61	Check SC 168		65	269.50	165.67	30.13
Check SC 3444		65	288.33	155.33	31.38	Check SC 3444		65	277.17	146.17	32.02
LSD 0.05		1	12.65	11.84	3.14	LSD 0.05		1	11.63	10.20	3.21

DSK: Days to 50% silking; PHT: Plant height (cm); EHT: Ear height (cm); GY: Grain yield (kg/ha); LSD 0.05: Least significant difference at 5% level of significance.

**Table 5. General combining ability (GCA) effects of inbred lines and testers in two sets for DSK, PHT, EHT, and GY across two locations.**

Set-1					Set-2				
Inbred	DSK	PHT	EHT	GY	Inbreds	DSK	PHT	EHT	GY
Inb. 01	-1.17**	-5.41	-4.54	-1.16	Inb. 22	-2.85**	-11.67**	-25.78**	-3.80**
Inb. 02	-0.42	4.84	-5.87	3.40**	Inb. 23	-1.26**	-7.51*	-13.45**	0.87
Inb. 03	-0.58*	-1.25	-6.79*	0.15	Inb. 24	-0.93**	1.16	-6.03**	0.19
Inb. 04	-0.75**	-0.83	-6.54*	-2.89**	Inb. 25	0.32	4.49	10.47**	-1.96*
Inb. 05	-1.08**	-7.75*	-14.71**	-2.56**	Inb. 26	0.32	-6.09*	-0.53	-2.72**
Inb. 06	-1.08**	-11.66**	-5.12	0.22	Inb. 27	1.15**	-11.09**	5.47*	-2.45**
Inb. 07	-0.08	11.09**	7.38*	7.21**	Inb. 28	-0.43	8.49**	10.47**	3.23**
Inb. 08	1.00**	3.92	-0.04	3.33**	Inb. 29	-0.18	-10.51**	-7.03**	1.86*
Inb. 09	-0.33	-2.08	-7.04*	1.42	Inb. 30	-0.43	-6.09**	-7.70**	-1.39
Inb. 10	1.25**	10.34**	8.63**	-1.78*	Inb. 31	2.40**	6.58**	25.47**	0.99
Inb. 11	-0.25	11.17**	10.38**	1.40	Inb. 32	0.32	18.33**	10.05**	5.83**
Inb. 12	-0.67*	-0.66	-2.29	0.43	Inb. 33	0.90**	1.08	2.63	2.61**
Inb. 13	0.42	-7.58*	-5.62	-1.85*	Inb. 34	-0.51	0.91	-6.28*	-3.54**
Inb. 14	0.50	9.25**	7.96*	2.62**	Inb. 35	0.65*	-4.51	-3.53	-2.94**
Inb. 15	0.17	-0.08	9.38**	-4.73**	Inb. 36	1.40**	-5.26	1.80	-1.34
Inb. 16	1.67**	-1.00	4.46	-1.82	Inb. 37	-0.18	2.91	-6.53*	2.62**
Inb. 17	0.33	8.17*	9.13**	-0.48	Inb. 38	0.57	4.16	-4.03	-0.32
Inb. 18	-0.08	-6.83*	-2.12	-2.51**	Inb. 39	0.07	5.66	3.97	1.57
Inb. 19	0.58*	-12.33**	4.79	-1.77	Inb. 40	-0.68*	-9.84**	-2.12	-3.31**
Inb. 20	-0.08	-5.00	-2.46	0.74	Inb. 41	0.32	4.74	8.47**	3.58**
Inb. 21	0.67*	3.67	1.04	0.64	Inb. 42	-1.01**	14.08**	4.22	0.41
S.E. gi	0.29	3.20	3.02	0.79	S.E. gi	0.32	2.93	2.58	0.81
S.E. gi-gj	0.41	4.52	4.27	1.12	S.E. gi-gj	0.45	4.15	3.65	1.14
T-1	-0.44**	6.92**	1.37	1.01**	T-1	-0.17	6.52**	0.90	2.04**
T-2	0.44**	-6.92**	-1.37	-1.01**	T-2	0.17	-6.52**	-0.90	-2.04**
S.E. gi	0.08	0.98	0.93	0.24	S.E. gi	0.09	0.90	0.79	0.25
S.E. gi-gj	0.12	1.39	1.32	0..34	S.E. gi-gj	0.13	1.28	1.12	0.35

\*, \*\*: Significant at the 0.05 and 0.01 probability levels, respectively.

DSK: Days to 50% silking; PHT: Plant height (cm); EHT: Ear height (cm); GY: Grain yield (ard/fed).

results are similar to those of Ismail *et al.* (2023a and 2024b). The positive and significant SCA effects for grain yield were observed, with hybrids H-17, H-19, H-22, H-33, H-39, H-42 in set-1 and H-46, H-51, H-55, H-59, H-63, H-66, H-73, H-76, H-80, H-82, and H-84 in set-2. From the previous results, the hybrids H-63 and H-73 showed desirable SCA effects on GY and significantly outyielded the best check, SC 3444, thereby emerging as promising hybrids for further evaluation and commercial use.

#### *Heterotic groups:*

Based on Vasal *et al.*, (1992), *inbred lines were assigned to heterotic groups* based on their specific combining ability (HSCA) effects for grain yield when crossed with two testers, Gm 6052 (A) and Gz.658 (B). In set-1, the inbred lines that showed negative SCA effects were grouped with their respective testers. Thus, inbreds such as Inb-01, 02, 04, 05, 07, 11, 12, 13, 14, 19, and Inb-21 were assigned to Group A (Tester GM.6052), while Inb-03, 06, 08, 09, 10,

**Table 6. Specific combining ability (SCA) effects of 84 hybrids in two sets for DSK, PHT, ear height EHT, and GY across two locations.**

		Set-1						Set-2			
Code	Hybrid	DSK	PHT	EHT	GY	Code	Hybrid	DSK	PHT	EHT	GY
H-01	Inb. 01 × T-1	0.60	2.75	-3.62	-1.53	H-43	Inb. 22 × T-1	-0.08	0.82	3.10	-1.13
H-02	Inb. 01 × T-2	-0.60	-2.75	3.62	1.53	H-44	Inb. 22 × T-2	0.08	-0.82	-3.10	1.13
H-03	Inb. 02 × T-1	-0.15	1.33	-4.62	-0.03	H-45	Inb. 23 × T-1	-0.33	3.15	-1.73	-3.46**
H-04	Inb. 02 × T-2	0.15	-1.33	4.62	0.03	H-46	Inb. 23 × T-2	0.33	-3.15	1.73	3.46**
H-05	Inb. 03 × T-1	0.85*	-11.59*	-5.54	1.75	H-47	Inb. 24 × T-1	0.34	-4.85	-1.82	1.82
H-06	Inb. 03 × T-2	-0.85*	11.59*	5.54	-1.75	H-48	Inb. 24 × T-2	-0.34	4.85	1.82	-1.82
H-07	Inb. 04 × T-1	-0.98*	-2.17	-0.62	-0.57	H-49	Inb. 25 × T-1	-0.24	-3.68	-5.48	-0.21
H-08	Inb. 04 × T-2	0.98*	2.17	0.62	0.57	H-50	Inb. 25 × T-2	0.24	3.68	5.48	0.21
H-09	Inb. 05 × T-1	-0.65	-3.92	-0.12	-1.41	H-51	Inb. 26 × T-1	-0.24	7.57	3.85	4.25**
H-10	Inb. 05 × T-2	0.65	3.92	0.12	1.41	H-52	Inb. 26 × T-2	0.24	-7.57	-3.85	-4.25**
H-11	Inb. 06 × T-1	0.52	10.00*	7.96	0.17	H-53	Inb. 27 × T-1	0.09	-5.43	0.02	-1.34
H-12	Inb. 06 × T-2	-0.52	-10.00*	-7.96	-0.17	H-54	Inb. 27 × T-2	-0.09	5.43	-0.02	1.34
H-13	Inb. 07 × T-1	0.35	-0.09	-0.20	-1.93	H-55	Inb. 28 × T-1	-0.16	3.65	4.85	2.66*
H-14	Inb. 07 × T-2	-0.35	0.09	0.20	1.93	H-56	Inb. 28 × T-2	0.16	-3.65	-4.85	-2.66*
H-15	Inb. 08 × T-1	0.44	2.08	3.55	1.36	H-57	Inb. 29 × T-1	-0.08	-1.85	1.18	0.95
H-16	Inb. 08 × T-2	-0.44	-2.08	-3.55	-1.36	H-58	Inb. 29 × T-2	0.08	1.85	-1.18	-0.95
H-17	Inb. 09 × T-1	-0.73	0.41	2.55	2.45*	H-59	Inb. 30 × T-1	-0.83	0.40	1.52	4.60**
H-18	Inb. 09 × T-2	0.73	-0.41	-2.55	-2.45*	H-60	Inb. 30 × T-2	0.83	-0.40	-1.52	-4.60**
H-19	Inb. 10 × T-1	1.69**	14.50**	11.05*	2.83*	H-61	Inb. 31 × T-1	-0.33	0.07	-0.48	0.27
H-20	Inb. 10 × T-2	-1.69**	-14.50**	-11.05*	-2.83*	H-62	Inb. 31 × T-2	0.33	-0.07	0.48	-0.27
H-21	Inb. 11 × T-1	0.02	-16.50**	-9.20*	-2.81*	H-63	Inb. 32 × T-1	-0.58	5.65	-0.90	2.59*
H-22	Inb. 11 × T-2	-0.02	16.50**	9.20*	2.81*	H-64	Inb. 32 × T-2	0.58	-5.65	0.90	-2.59*
H-23	Inb. 12 × T-1	-1.06**	-5.34	-4.70	-1.91	H-65	Inb. 33 × T-1	0.17	5.07	0.85	-2.82*
H-24	Inb. 12 × T-2	1.06**	5.34	4.70	1.91	H-66	Inb. 33 × T-2	-0.17	-5.07	-0.85	2.82*
H-25	Inb. 13 × T-1	-0.31	0.91	-1.37	-2.03	H-67	Inb. 34 × T-1	0.26	-8.60*	-11.23**	0.15
H-26	Inb. 13 × T-2	0.31	-0.91	1.37	2.03	H-68	Inb. 34 × T-2	-0.26	8.60*	11.23**	-0.15
H-27	Inb. 14 × T-1	0.60	3.41	0.71	-0.13	H-69	Inb. 35 × T-1	1.09*	9.82*	8.85*	1.90
H-28	Inb. 14 × T-2	-0.60	-3.41	-0.71	0.13	H-70	Inb. 35 × T-2	-1.09*	-9.82*	-8.85*	-1.90
H-29	Inb. 15 × T-1	-0.73	-3.42	-0.20	1.74	H-71	Inb. 36 × T-1	0.01	-0.60	0.35	-1.00
H-30	Inb. 15 × T-2	0.73	3.42	0.20	-1.74	H-72	Inb. 36 × T-2	-0.01	0.60	-0.35	1.00
H-31	Inb. 16 × T-1	0.27	0.50	-1.62	0.50	H-73	Inb. 37 × T-1	0.09	13.07**	10.52**	5.90**
H-32	Inb. 16 × T-2	-0.27	-0.50	1.62	-0.50	H-74	Inb. 37 × T-2	-0.09	-13.07**	-10.52**	-5.90**
H-33	Inb. 17 × T-1	-0.23	3.33	4.71	2.86*	H-75	Inb. 38 × T-1	-0.33	-10.52*	-10.65**	-2.31*
H-34	Inb. 17 × T-2	0.23	-3.33	-4.71	-2.86*	H-76	Inb. 38 × T-2	0.33	10.52*	10.65**	2.31*
H-35	Inb. 18 × T-1	-1.31**	1.00	0.46	1.70	H-77	Inb. 39 × T-1	-0.66	-2.68	0.68	0.19
H-36	Inb. 18 × T-2	1.31**	-1.00	-0.46	-1.70	H-78	Inb. 39 × T-2	0.66	2.68	-0.68	-0.19
H-37	Inb. 19 × T-1	0.85*	-6.34	-3.29	-1.82	H-79	Inb. 40 × T-1	1.09*	-4.35	0.93	-2.58*
H-38	Inb. 19 × T-2	-0.85*	6.34	3.29	1.82	H-80	Inb. 40 × T-2	-1.09*	4.35	-0.93	2.58*
H-39	Inb. 20 × T-1	0.02	6.66	4.30	2.42*	H-81	Inb. 41 × T-1	0.42	-5.43	-4.98	-6.53**
H-40	Inb. 20 × T-2	-0.02	-6.66	-4.30	-2.42*	H-82	Inb. 41 × T-2	-0.42	5.43	4.98	6.53**
H-41	Inb. 21 × T-1	-0.06	2.50	-0.20	-3.62**	H-83	Inb. 42 × T-1	0.26	-1.27	0.60	-3.88**
H-42	Inb. 21 × T-2	0.06	-2.50	0.20	3.62**	H-84	Inb. 42 × T-2	-0.26	1.27	-0.60	3.88**
S.E SCA		0.41	4.52	4.27	1.26	S.E SCA		0.45	4.15	3.65	1.14
S.E. Sij-Sik		0.58	6.40	6.05	1.59	S.E. Sij-Sik		0.64	5.87	5.17	1.62

\*, \*\*: Significant at the 0.05 and 0.01 probability levels, respectively.

DSK: Days to 50% silking; PHT: Plant height (cm); EHT: Ear height (cm); GY: Grain yield (ard/fed).

**Table 7. Heterotic grouping of 42 inbred lines in two sets based on specific combining ability (SCA) effects for grain yield across two locations**

Set-1				Set-2			
Inbred line	Tester Gm.6052 (A)	Tester GZ.658 (B)	Heterotic Group	Inbred line	Tester Gm.6052 (A)	Tester GZ.658 (B)	Heterotic Group
	SCA	SCA			SCA	SCA	
Inb. 01	-1.53	1.53	A	Inb. 22	-1.13	1.13	A
Inb. 02	-0.03	0.03	A	Inb. 23	-3.46**	3.46**	A
Inb. 03	1.75	-1.75	B	Inb. 24	1.82	-1.82	B
Inb. 04	-0.57	0.57	A	Inb. 25	-0.21	0.21	A
Inb. 05	-1.41	1.41	A	Inb. 26	4.25**	-4.25**	B
Inb. 06	0.17	-0.17	B	Inb. 27	-1.34	1.34	A
Inb. 07	-1.93	1.93	A	Inb. 28	2.66*	-2.66*	B
Inb. 08	1.36	-1.36	B	Inb. 29	0.95	-0.95	B
Inb. 09	2.45*	-2.45*	B	Inb. 30	4.60**	-4.60**	B
Inb. 10	2.83*	-2.83*	B	Inb. 31	0.27	-0.27	B
Inb. 11	-2.81*	2.81*	A	Inb. 32	2.59*	-2.59*	B
Inb. 12	-1.91	1.91	A	Inb. 33	-2.82*	2.82*	A
Inb. 13	-2.03	2.03	A	Inb. 34	0.15	-0.15	B
Inb. 14	-0.13	0.13	A	Inb. 35	1.90	-1.90	B
Inb. 15	1.74	-1.74	B	Inb. 36	-1.00	1.00	A
Inb. 16	0.5	-0.5	B	Inb. 37	5.90**	-5.90**	B
Inb. 17	2.86*	-2.86*	B	Inb. 38	-2.31*	2.31*	A
Inb. 18	1.7	-1.7	B	Inb. 39	0.19	-0.19	B
Inb. 19	-1.82	1.82	A	Inb. 40	-2.58*	2.58*	A
Inb. 20	2.42*	-2.42*	B	Inb. 41	-6.53**	6.53**	A
Inb. 21	-3.62**	3.62**	A	Inb. 42	-3.88**	3.88**	A

15, 16, 17, 18, and Inb-20 were assigned to Group B (Tester GZ.658). In set-2, the group A included Inb-22, 23, 25, 27, 33, 36, 38, 40, 41, and Inb-42, while Inb-24, 26, 28, 29, 30, 31, 32, 34, 35, 37, and Inb-39 were placed in Group B (Table 7).

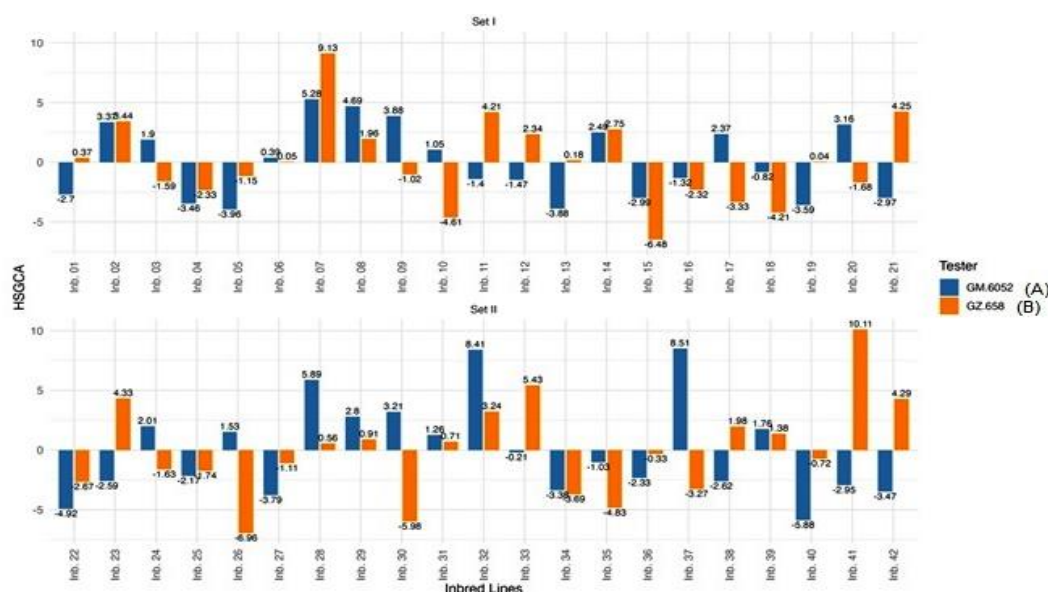
The heterotic group-specific and general combining ability (HSGCA) method, which integrates specific (SCA) and general combining abilities (GCA) for more robust classification is presented in (Table 8 and figure 2 ) according to Fan *et al.*, (2009), the inbred lines, were assigned to a group based on the highest negative HSGCA value with a tester while the inbred lines with positive HSGCA with both testers remain ungrouped. In set 1, the inbreds 1, 4, 5, 11, 12, 13, 19, and Inb-21 were classified into group A, while group B included Inb-3, 9, 10, 15, 16, 17, 18, and Inb-20. However, the inbred lines 2, 6, 7, 8, and Inb-14 were considered ungrouped. In set 2, group A comprised 10 inbred lines: 22, 23, 25, 27, 33, 36, 38, 40, 41, and 42, while

group B consisted of 6 inbred lines: 24, 26, 30, 34, 35, and 37; however, the inbreds 28, 29, 31, 32, and Inb-39 remained ungrouped.

Classification of inbred lines into heterotic groups by the HGCAMT method, according to Badu-Apraka *et al.*, (2013), the dendrogram for Set 1 (Figure 3) revealed the genetic relationships among the inbred lines and testers based on GCA effects across multiple traits. Two major clusters had much lower R-squared values (around 0.3), indicating substantial genetic divergence between them. The first cluster contains inbred lines 01, 02, 03, 04, 05, 06, 09, 12, and 20, along with the tester GM-6052. This cluster showed high within-group similarity, as indicated by R-squared values above 0.7, suggesting that these inbreds may be considered a heterotic group (Group A). The second central cluster comprises inbred lines 07, 08, 10, 11,

**Table 8. Heterotic grouping of 42 maize inbred lines in two sets based on the combined specific and general combining ability (HSGCA) method for grain yield across two locations.**

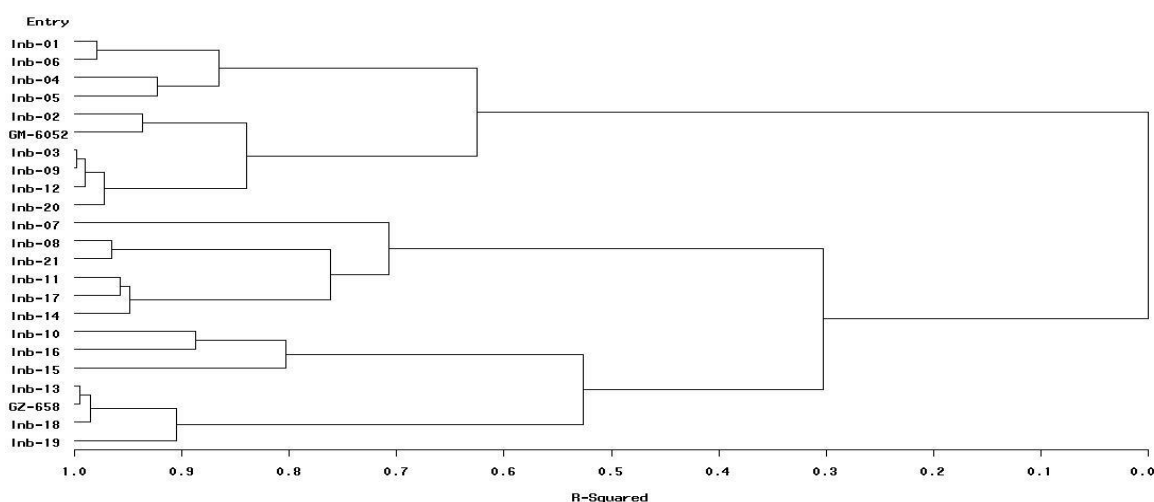
Set-1				Set-2			
Inbred line	HSGCA		Heterotic group	Inbred line	HSGCA		Heterotic group
	GM.6052 (A)	GZ.658 (B)			GM.6052 (A)	GZ.658 (B)	
Inb. 01	-2.70	0.36	A	Inb. 22	-4.92	-2.67	A
Inb. 02	3.37	3.43	-	Inb. 23	-2.59	4.33	A
Inb. 03	1.90	-1.59	B	Inb. 24	2.01	-1.63	B
Inb. 04	-3.46	-2.33	A	Inb. 25	-2.17	-1.74	A
Inb. 05	-3.96	-1.15	A	Inb. 26	1.53	-6.96	B
Inb. 06	0.39	0.05	-	Inb. 27	-3.79	-1.11	A
Inb. 07	5.28	9.13	-	Inb. 28	5.89	0.56	-
Inb. 08	4.69	1.96	-	Inb. 29	2.80	0.91	-
Inb. 09	3.88	-1.02	B	Inb. 30	3.21	-5.98	B
Inb. 10	1.05	-4.61	B	Inb. 31	1.26	0.71	-
Inb. 11	-1.40	4.21	A	Inb. 32	8.41	3.24	-
Inb. 12	-1.47	2.34	A	Inb. 33	-0.21	5.43	A
Inb. 13	-3.88	0.18	A	Inb. 34	-3.38	-3.69	B
Inb. 14	2.49	2.75	-	Inb. 35	-1.03	-4.83	B
Inb. 15	-2.99	-6.48	B	Inb. 36	-2.33	-0.33	A
Inb. 16	-1.32	-2.32	B	Inb. 37	8.51	-3.27	B
Inb. 17	2.37	-3.33	B	Inb. 38	-2.62	1.98	A
Inb. 18	-0.82	-4.21	B	Inb. 39	1.76	1.38	-
Inb. 19	-3.59	0.04	A	Inb. 40	-5.88	-0.72	A
Inb. 20	3.16	-1.68	B	Inb. 41	-2.95	10.11	A
Inb. 21	-2.97	4.25	A	Inb. 42	-3.47	4.29	A



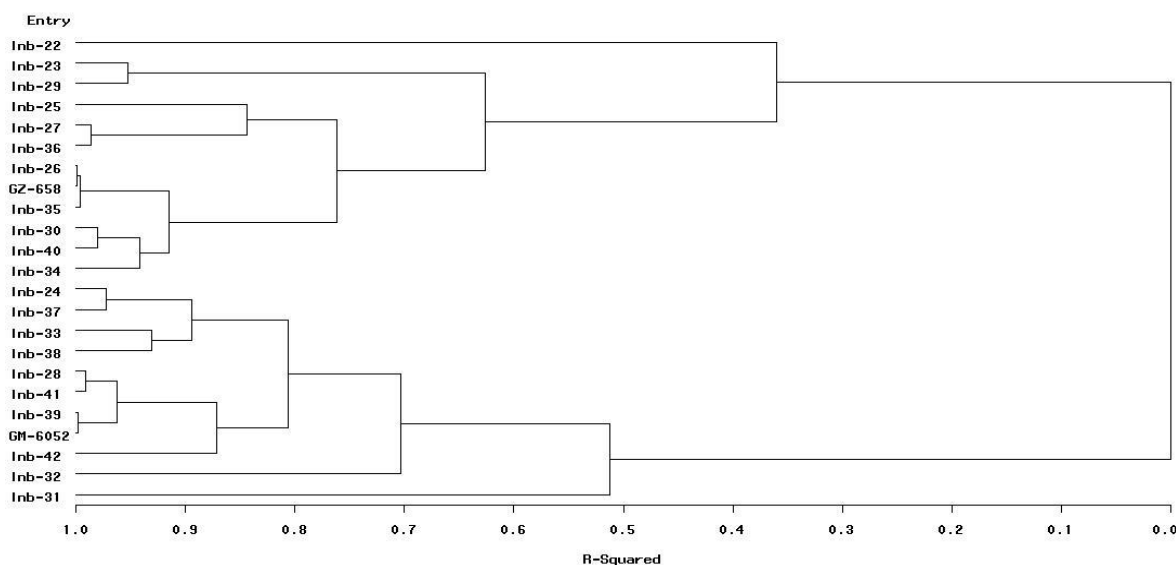
**Figure 2. Specific and general combining ability (HSGCA) values of inbred lines with testers GM.6052 and GZ.658 in set-1 and set-2 for grain yield.**

13, 14, 15, 16, 17, 18, 19, and 21, with the tester GZ-658. The R-squared values within this cluster are similarly high, reflecting strong genetic affinity among its members (Group B). For Set 2 (Figure 4), the dendrogram also showed two major clusters. The first cluster includes inbreds 22, 23, 25, 26, 27, 29, 30, 34, 35, 36, and 40, with tester GZ-658(A). The high R-squared values (above 0.8) within this group indicate substantial genetic similarity and the potential for this cluster to serve as a primary heterotic group. The second cluster, consisting of inbreds 24,

28, 31, 32, 33, 37, 38, 39, 41, and 42, is more distinct and separated from the leading group at a lower R-squared value (approximately 0.4–0.5), highlighting its genetic uniqueness. The clear separation between these clusters, as quantified by the R-squared metric, underlines the genetic diversity present within set 2 and supports the strategic use of these groupings in hybrid breeding to maximise heterosis. Notably, differences in inbred group assignments by HGCAMT compared to HSCA and HSGCA methods.



**Figure 3. Dendrogram of 21 maize inbred lines (Set I) based on general combining ability (GCA) effects for grain yield and other traits (HGCAMT), constructed using Ward's minimum variance method.**



**Figure 4. Dendrogram of 21 maize inbred lines (Set 2) based on general combining ability (GCA) effects for grain yield and other traits (HGCAMT), constructed using Ward's minimum variance method.**

### Comparison between the three heterotic groups' methods.

The three heterotic groups' methods, HSCA, HSGCA, and HGCAMT, showed significant differences in identifying high-yielding hybrids across the two sets of lines. HSGCA identified the highest number of inter-group crosses (18), compared to HSCA (14) and HGCAMT (11) for the high-yield group (28.82 – 36.95 ard/fed) in set 1. Notably, HSGCA had no intra-group crosses in this high-yield group, while HSCA had 4 and HGCAMT had 8 (Table 9). Similarly, HSGCA again identified the most inter-group crosses (15), followed closely by HGCAMT (14) and HSCA (11) for the high-yield group (25.82 – 36.36 ard/fed) in set 2 (Table 10). According to Fan *et al.*, (2009), *an effective heterotic group method should identify groups in which inter-group crosses exhibit higher heterosis than intra-group crosses*. Thus, the HSGCA method proved to be the most effective for classifying inbreds into heterotic groups, followed by the HSCA and HGCAMT methods. The comparative showed that the HSGCA method is the most effective for heterotic grouping in yield-

oriented breeding programs, while HGCAMT offers complementary insights by capturing broader genetic relationships, beneficial for multi-trait improvement. These findings align with those of Fan *et al.*, (2009), Badu-Apraku *et al.*, (2013 and 2015), Akinwale *et al.*, (2014), Amegbor *et al.*, (2017), Olayiwola (2021), Ribeiro *et al.*, (2023), and Mosa *et al.*, (2024), They concluded that the superior efficiency of HSGCA over HSCA in classifying inbred lines into heterotic groups. Similarly, Ismail *et al.* (2022, 2023) also reported the effectiveness of HSGCA in accurately assigning inbreds to their respective heterotic groups.

### Breeding efficiency:

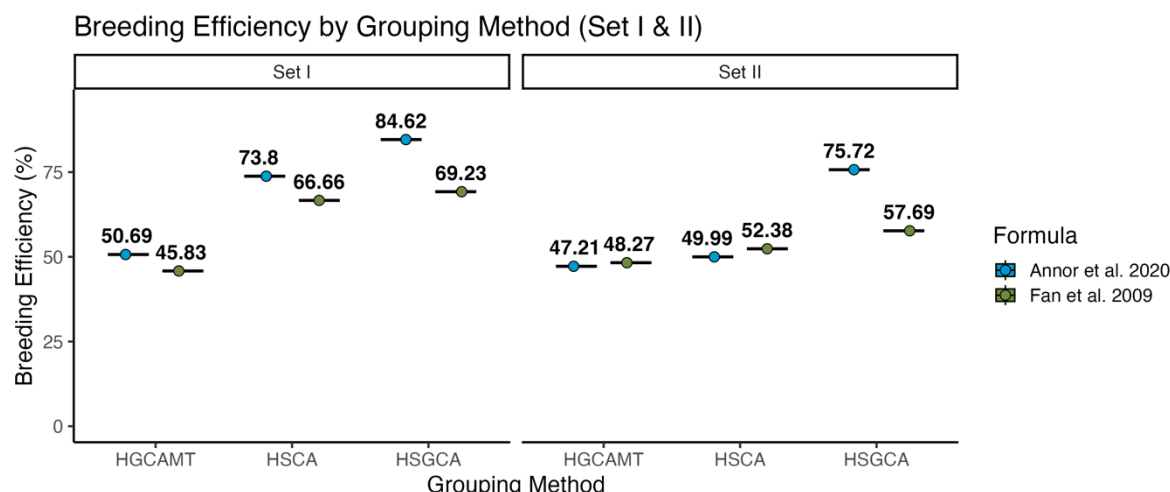
Figure 5 shows the breeding efficiency % according to Fan *et al.*, (2009) and Annor *et al.*, (2020) for three methods. Set-1 showed the superiority of the HSGCA method, with the highest efficiencies of 69.23% for Fan and 84.62% for Annor. HSCA showed intermediate efficiency (66.66% for Fan, 73.80% for Annor), while HGCAMT recorded the lowest values (45.83% for Fan, 50.69% for Annor). Similarly, in Set 2, HGCAMT exhibited lower efficiency (48.27% of Fan, 47.21% of

**Table 9. Breeding efficiency% of three heterotic groups methods, for grain yield in set 1.**

Yield group	Cross type	Set 1		
		HSCA	HSGCA	HGCAMT
28.82-36.95 ard/fed	Inter-group	14	18	11
	Intra-group	4	0	8
21.33-28.82 ard/fed	Inter-group	7	8	13
	Intra-group	17	16	10
No of Inter-group		21	26	24
No of Intra-group		21	16	18
Breeding efficiency (Fan <i>et al.</i> , 2009)		66.66	69.23	45.83
Breeding efficiency (Annor <i>et al.</i> , 2010)		73.80	84.62	50.69

**Table 10. Breeding efficiency (%) of three heterotic group methods for grain yield in Set2.**

Yield group	Cross type	Set 2		
		HSCA	HSGCA	HGCAMT
25.82-36.36 ard/fed	Inter-group	11	15	14
	Intra-group	0	1	7
16.81-25.81 ard/fed	Inter-group	10	11	15
	Intra-group	21	15	6
No of Inter-group		21	26	29
No of Intra-group		21	16	13
Breeding efficiency (Fan <i>et al.</i> , 2009)		52.38	57.69	48.27
Breeding efficiency (Annor <i>et al.</i> , 2010)		49.99	75.72	47.21



**Figure 5. Breeding efficiency% of three heterotic groups methods for Set-1 and Set-2.**

Annor) compared to HSGCA (57.69% Fan, 75.72% Annor) and HSCA (52.38% of Fan, 49.99% of Annor). As a result, the Annor method is generally regarded as more robust and informative for measuring breeding efficiency in a heterotic group (Fan *et al.*, 2009; Badu-Apraku *et al.*, 2013).

## CONCLUSION

This study identified the tester GM. 6052 is a good combiner for earliness and yield. While the tester GZ.658 displayed favourable GCA effects for plant height. Notably, Inb-02, Inb-07, Inb-08 and Inb-32 demonstrated significant positive GCA effects and were emerged as good combiners for grain yield to improve grain yield. Furthermore, the study indicated that the HSGCA method provided the highest breeding efficiency and most accurately predicted superior inter-group hybrids, followed by (HSCA) and (HGCAMT).

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