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COMBINING ABILITY AND HETEROTIC EFFECTS IN YELLOW MAIZE FOR MORPHOLOGICAL AND YIELD COMPONENTS

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SUMMARY

The success of hybrid maize (*Zea mays* L.) breeding depends on understanding the combining ability effects of the inbred lines. The study aimed to evaluate the general combining ability (GCA), specific combining ability (SCA), and heterotic effects in yellow maize for various traits. Ten inbred lines' crossing with three testers used the line-by-tester mating scheme. The resulting 30 F_1 hybrids underwent evaluation against two check genotypes in a randomized complete block design (RCBD) with three replications during the kharif growing season of 2021 at the Cereal Crop Research Institute (CCRI), Nowshehra, Pakistan. Significant heterotic and combining effects were evident for the studied traits. Inbred lines YL-02 and YL-06 showed significant positive GCA for ear length, 100-grain weight, and grain yield. The F_1 hybrids YL-02 × YD-04 (8209.6 kg ha^{-1}) and YL-01 × YL-07 RC (6979.6 kg ha^{-1}) revealed maximum grain yield and significant positive SCA effects, indicating potential for yield improvement. Estimates of SCA were greater than GCA for all the studied traits, signifying the importance of the non-additive gene action in the inheritance of studied traits. Based on combing ability effects and yield performance, the F_1 crosses YL-02 × YD-04 and YL-01 × YL-07 RC are desirable for future breeding programs.

Keywords: Maize (*Z. mays* L.), hybrids, mean performance, combining ability, heterosis, heterobeltiosis, grain yield, gene action.

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Key findings: The maize (*Z. mays* L.) inbred lines YL-01, YL-02, and YL-06 emerged with desirable and significant GCA effects. The F_1 hybrids YL-02 × YD-04 and YL-01 × YL-07 RC exhibited with significant SCA effects and maximum grain yield. These parents and hybrids could be beneficial in future hybridization programs of yellow maize.

INTRODUCTION

The cultivated maize (*Zea mays* L., 2n=2x=20) ranks third in cereals after wheat and rice in the world (Jatto *et al.,* 2024). Maize is native to America and originated almost 7000 years ago from there (Prufer *et al.,* 2021). Regarding production, it has the largest average yield per unit area among the cereals. Its growing is mainly for food and feed purposes. Its grains are also suitable as raw materials in the production of edible oil, starches, and several other byproducts (Ismail *et al.,* 2020).

Maize cultivation covers an estimated area of 197 million hectares worldwide with an annual production of 1,137 million tons (Li *et al.,* 2025). In Pakistan, the area under maize crop comprised 1.6 million hectares, with a total production of 9.8 million tons and an average yield of 5,960 kg ha^{-1}. Maize contributed 0.71% toward Pakistan's GDP and has the potential to enhance food security (Pakistan Bureau of Statistics, 2023–2024). The average yield production of maize per hectare is still below the global production due to various biotic (insect pests, diseases, and weeds) and abiotic (temperature, rainfall, and soil fertility) factors. It has the highest potential gap on a national level, and to fill this yield gap requires using locally available germplasm to increase grain yield of the maize crop (Khan *et al.,* 2021).

Food insecurity is a serious threat to public health, social, and political sustainability. This threat becomes magnified due to climate change and increasing global population, which tends to increase up to 10 billion in the next 50 years. Proper management of available diversity in maize crops is considerably the basic step toward its yield improvement (Aliyu *et al.,* 2021; Wudil *et al.,* 2022).

Hybrid breeding is one of the best choices for its achievement; hence, information regarding the estimation of the combining ability of the inbred lines is very significant (Belay, 2022). Combining ability analysis is one of the most widely used methods for identifying and selecting superior inbred lines and cross combinations for the development of hybrid vigor (Badu *et al.,* 2021), and heterosis expresses superior performance versus parental plants or lines (Paril *et al.,* 2024).

In the present era of molecular and modern techniques, the line x tester analysis has still retained its prominence. It is a reliable and efficient technique and can be effective for identifying suitable lines and F_1 hybrids (Parameshwarappa *et al.,* 2021). The presented study aimed to estimate combining abilities to identify better parents and F_1 hybrids using the line-by-tester breeding scheme.

MATERIALS AND METHODS

Ten yellow maize inbred lines (YD-01, YD-02, YL-01, YL-02, YL-04, YL-05, YL-06, YL-08 RC, HCN-113, and AML-13) and three testers (YD-04, China-11, and YL-07 RC) incurred selection based on their distinct characters and yield performance (Table 1). All these 10 inbred lines underwent crossing with three testers in the line x tester breeding pattern at CCRI, Pirsabak (Nowshehra), Pakistan. The resulting 30 F_1 crosses, along with their parents, proceeded to further evaluation in a randomized complete block design (RCBD) with three replications during the kharif growing season of 2021. All the recommended field practices (irrigation, fertilization, and pesticides/weedicides spraying) for maize crop progressed to obtain better yield. From each replicated plot, 10 plants' random selection had their data recorded on various traits. Recording the number of days to anthesis, days to silking, plant height, ear length, ear diameter, and 100-grain weight continued as per procedures described by Tesfaye *et al.* (2019).

Table 1. Parentage details and distinctive features of the breeding materials.

Parents	Pedigree/Parentage	Distinctive Features		
Inbred Lines		Maturity	Plant height	Yield
YD-1	YC-02 x YC-05	Early maturity	Moderate	High
YD-2	YC-02 x YC-06	Late maturity	Dwarf	Moderate
YL-1	YC-03 x YD-05 x YH-04	Late maturity	Moderate	High
YL-2	YC-03 x YD-07 x YH-03	Late maturity	Moderate	High
YL-4	YC-05 x YD-08	Late maturity	Tall	Moderate
YL-5	YC-05 x YD-08 x YH-04	Late maturity	Moderate	High
YL-6	YC-05 x YD-08 x YH-07	Early maturity	Moderate	Moderate
YL-8 RC	YH-04 x YH-07	Early maturity	Dwarf	Moderate
HCN-113	TRH-12 x RCH-02	Late maturity	Dwarf	High
AML-113	TRH-12 x RCH-04	Early maturity	Tall	High
Testers		Pollen production(PP)/ maturity	Plant height	Yield
YD-4	YC-03 x YC-09	Better PP, Late maturity	Moderate	High
China-11	CH-05 x CH-13	Better PP, Early maturity	Dwarf	Moderate
YL-7 RC	YH-04 x YH-06	Better PP, Late maturity	Moderate	High

Table 2. Analysis of variance for morphological, yield, and yield-related traits in yellow maize.

S.O.V.	Days to anthesis	Days to silking	Plant height (cm)	Ear length (cm)	Ear diameter (cm)	100-grain weight (g)	Grain yield (kg ha^{-1})
Replications	1.5	0.05	22.6	0.38	0.03	2.6**	59658.3
Genotypes	28.1**	26.8**	819.1**	11.1**	0.21**	28.9**	7817326**
Parents	53.5**	53.7**	1518.1**	10.4**	0.37**	27.2**	8569441**
Parents vs Crosses	5.6**	7.2**	7869.6**	71.1**	0.04	45.2**	24210712**
Crosses	16.7**	14.5**	238.5**	9.5**	0.13	29.1**	6888946**
Lines	15.1	12.8	172.1	14.8*	0.07	48.5*	10098862
Testers	42	34.2	18.1	14.1	0.23	16.9	5067454
Line x Tester	14.6**	13.2**	296.1**	6.3**	0.16*	20.7**	5486377**
Error	0.86	0.58	7.8	0.36	0.03	0.48	37832.5
CV (%)	1.4	1.1	2.1	3.9	4.9	3.6	4.4

** and *: Significant at 1% and 5% probability levels.

The calculation of grain yield ha^{-1} used the following equation (Khalil *et al.,* 2011).

$$Grain\ Yield\ \left(\frac{kg}{hectare}\right) = \frac{FEW\ (kg)\ x\ (100 - GMC)\ x\ 0.8\ x\ 10000}{(100 - 15)\ x\ Area\ Harvested\ (m^2)}$$

Where: FEW = Fresh ear weight, GMC = Grain moisture content, and 0.8 = Shelling coefficient of maize.

Statistical analysis

Data collected for all parameters sustained the analysis of variance (Usman *et al.,* 2024). Line x tester analysis transpired by the open-source R-statistical software version 3.0.1 using the agricolae package per the standard method given by Kempthorne (Islam *et al.*, 2022). Heterotic effects' calculation for each studied character succeeded, with t-tests used to check the significance of mid-parent and better-parent heterosis (Daif *et al.,* 2024).

a. $\text{“}t\text{” for mid} - \text{parent heterosis} \;=\; (F_1 - MP)/\sqrt{3/2r \times \delta_E^2}$

b. $\text{“}t\text{” for better} - \text{parent heterosis} \;=\; (F_1 - BP)/\sqrt{2/r \times \delta_E^2}$

RESULTS AND DISCUSSION

Mean performance and heterosis

The analysis of variance showed significant differences among the parents, crosses, parents vs. crosses, and line × tester for all studied traits (Table 2). Crosses' mean square values were highly significant for all studied traits {days to anthesis [16.7], days to silking [14.5], plant height [238.5], ear length [9.5], 100-grain weight [29.1], and grain yield [6,888,946]} except ear diameter (0.13). One can deduce that sufficient genetic variability was present among the parents and F_1 crosses for the studied traits; hence, selection of the most desirable crosses would be possible.

Extremely significant variation was evident among all the genotypes (parents and crosses) from the mean values for all studied traits (Table 3). Mid-parent and better-parent heterosis were also highly substantial for all traits (Table 04). Regarding grain yield ha^{-1}, YL-02 × YD-04 (8,209.6 kg ha^{-1}) performed better than the best check variety, Edhi, with a maximum mid-parent (164.4%) and better-parent (155.5%) heterotic effects for the studied trait. For the 100-grain weight, YL-02 × YD-04 (25.3 g) exhibited the maximum mean value. Significant mid-parent (38.1%) and better-parent (26.9%) heterotic effects for 100-grain weight resulted in the F_1 hybrids YL-02 × YD-04 and HCN-113 × YL-07 RC, respectively. Higher grain weight contributes more to the total weight of the harvested grain (Raihan *et al.,* 2021). Results of the current research study conform to the findings of Moneam *et al.* (2022). Regarding days to anthesis and days to silking, the F_1 crosses YL-02 × China-11 and YL-01 × YL-07 RC were highly significant toward earliness. For days to anthesis, significant and desirable negative mid-parent (-9.8%) and better-parent heterosis (-9.8%) emerged for the F_1 hybrid YL-01 × YL-07 RC. Meanwhile, for days to silking, desirable mid-parent heterosis manifested for YL-01 × YL-07 RC (-8.9%). Expression of negative heterosis in hybrids for days to anthesis and silking is highly desirable, as it is an indication of early maturity, which is employable for breeding of early-maturing maize hybrids. Subba *et al.* (2022) reported significant and negative heterosis for days to anthesis and silking, which agreed with the presented results.

For plant height, highly significant and desirable mid-parent and better-parent heterosis was notable for YL-04 × YD-04 (-2.9%) and YD-01 × YD-04 (-7.7%), respectively. Plant breeders are keen to develop semi-dwarf hybrids of maize crops. Negative heterosis is favorable for plant height, as it can help reduce lodging problems in maize crops (Jiao *et al.,* 2023). Results of this study aligned with the findings of the study conducted by Subba *et al.* (2022). Regarding ear length, the maximum value was visible for YL-01 × YD-04 (19.7 cm). Significant and maximum mid-parent (59.9%) and better-parent (53.1%) heterosis for ear length appeared for the F_1 hybrid YL-06 × YD-04. Zendrato *et al.* (2024) observed remarkable variations and heterotic effects for ear length among the tested genotypes, which was confirmatory with this promising research finding.

General combining ability

The estimation of combining ability effects (GCA and SCA) ensued for all the parental lines and F_1 hybrids. Estimates of GCA of the parental lines and testers were significant for all studied traits of yellow maize, except ear diameter (Table 5). Regarding days to anthesis, days to silking, ear length, and 100-grain weight, the inbred line YL-02 revealed significant GCA effects. Inbred lines having desirable negative GCA for days to anthesis and silking can be suitable for earliness. Inbred lines with negative GCA effects for days to anthesis and silking are the best candidates for early maturity (Belay, 2022). The inbred lines with advantageous positive GCA effects for ear length can be beneficial in hybrid breeding programs to enhance maize grain yield (Kamara and Qabil, 2019). Regarding grain yield ha^{-1}, YL-06 revealed significant and maximum positive GCA effects. Mosa *et al.* (2021) reported positive GCA effects of the inbred lines for 100-grain weight and grain yield.

Specific combining ability

Estimates of SCA effects were also significant for all studied traits, except ear diameter (Table 6). For days to anthesis and days to silking, almost half of the total crosses revealed considerable and negative SCA

Table 3. Mean performance of lines, testers, and crosses for morphological, yield, and yield-related traits in yellow maize.

Lines	Days to anthesis	Days to silking	Plant height (cm)	Ear length (cm)	Ear diameter (cm)	100-grain weight (g)	Grain yield (kg ha^{-1})
YD-1	58	59	112.9	15.3	3.8	23	3479
YD-2	60	61	78.3	13.2	4	15.1	2651
YL-1	61	63	115.7	15	3.6	20.2	2767.3
YL-2	61	62	122.7	13.9	3.6	20.8	2972.1
YL-4	61	63	120	12.3	3.9	19	2826.4
YL-5	61	63	124.1	15	3.9	17	2989.6
YL-6	55	56	110.2	11.3	3.8	27.4	2677.3
YL-8 RC	58	58	80.4	9	3.6	13.4	2558.7
HCN-113	61	63	78.1	15.1	4	16.7	3093.9
AML-113	58	59	139.7	15.6	4	20.5	3172.7
Testers							
YD-4	60	61	125	10.4	3.8	15.8	3008.3
China-11	58	60	88.3	13.6	4	16.4	2617.1
YL-7 RC	61	63	115.4	14	4.1	17.6	2724.1
Crosses							
YD-01 x YD-4	58	62	114.4	15.3	3.9	22.6	5266.1
YD-2 x YD-4	57	58	121.2	14.4	4	18	3278.6
YL-1 x YD-4	61	62	151.1	19.7	3.8	20.4	3756.9
YL-2 x YD-4	56	58	144.8	19.4	3.7	25.3	8209.6
YL-4 x YD-4	60	62	118.4	13.4	3.7	22.6	4258.6
YL-5 x YD-4	60	62	133.4	13.7	3.7	16.3	3703.6
YL-6 x YD-4	60	62	118.1	17.9	4.1	23.2	7267
YL-8 RC x YD-4	58	60	127.4	14.3	3.9	18.1	3553.4
HCN-113 x YD-4	58	58	126.9	14.8	3.9	15.4	3934.8
AML-113 x YD-4	57	59	134.2	18.0	3.8	21	5790.5
YD-01 x China-11	59	61	131.2	13.3	3.8	19.2	3563.4
YD-2 x China-11	59	61	129.2	14	4.1	16.6	3540.3
YL-1 x China-11	59	59	119.3	13.3	4	19.2	2883.9
YL-2 x China-11	55	57	136.2	15.8	4.2	22.7	3846
YL-4 x China-11	55	57	142.9	16.4	4	21.3	6423.3
YL-5 x China-11	60	62	120.4	16.2	4	18	3678.2
YL-6 x China-11	58	60	124.8	16.1	3.8	19.7	6582.2
YL-8 RC x China-11	57	59	144.1	14.4	3.9	20.2	4291.8
HCN-113 x China-11	57	57	121.8	13.2	3.8	17.8	3364.3
AML-113 x China-11	58	60	133.1	13.3	3.8	14.4	4025.6
YD-01 x YL-07 RC	63	64	121.6	13.1	3.8	15.2	2703.4
YD-2 x YL-07 RC	64	66	136.9	13.9	3.7	19.1	3332.4
YL-1 x YL-07 RC	55	58	120	16.7	4	23.5	6979.6
YL-2 x YL-07 RC	57	59	135.2	15.3	3.9	24.8	4383.2
YL-4 x YL-07 RC	61	62	128.6	12.3	3.5	23.1	3529.1
YL-5 x YL-07 RC	58	60	145.2	14.2	4.1	20.1	3835.1
YL-6 x YL-07 RC	57	59	131.4	16.2	4	18.1	6414.2
YL-8 RC x YL-07 RC	56	59	120.9	14.2	3.4	16.2	3768.8
HCN-113 x YL-07 RC	60	62	127.3	14.3	3.6	22.2	3635.5
AML-113 x YL-07 RC	59	61	131.2	16.3	3.9	16.6	3330.7
Checks							
30Y87	57	60	153	17.6	4.6	20.5	7149.6
Edhi	59	61	140.1	16.4	4	18.3	7911.1

Table 4. Mid-parent and better-parent heterotic effects for morphological, yield, and yield-related traits in yellow maize hybrids.

F_1 Hybrids	Days to anthesis		Days to silking		Plant height (cm)		Ear length (cm)		Ear diameter (cm)		100-grain weight (g)		Grain yield (kg ha^{-1})	
	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH
YD-01 x YD-4	-1.7*	0	2.2**	3.9**	-2.6**	-7.7**	21.9**	4.3*	4.5	4.5	15.9**	-1.9	59.1**	49.7**
YD-2 x YD-4	-5**	-5**	-4.9**	-4.9**	18.4**	-3.5**	19.6**	8.7**	0.91	-2.6	17.3**	14.5**	10.5**	2.1
YL-1 x YD-4	0.83	1.7*	0	1.6*	25.9**	19.6**	52.9**	31.8**	-2.4	-4.2	14.6**	2.5	33.1**	25.5**
YL-2 x YD-4	-7.4**	-6.7**	-5.7**	-4.9**	16.7**	14.4 **	57.1**	40.6**	4.6	2.9	38.1**	21.6**	164.4**	155.5**
YL-4 x YD-4	-0.83	0	-0.54	0.54	-2.9**	-4.9**	17.1**	10.2**	-3.6	-4.9	32.3**	22.1**	39.3**	32.9**
YL-5 x YD-4	-0.83	0	0.54	1.6*	4.1**	2.7*	8.3**	-6.6**	-2.2	-3.6	-1.4	-4.6	19.8**	15.6**
YL-6 x YD-4	4.4**	9.1**	5.9**	10.7**	-0.20	-6.2**	59.9**	53.1**	8.5	6.8	11.8**	-10.1**	142.1**	125.9**
YL-8 RC x YD-4	-1.7*	0	-0.28	2.3**	21.9**	0.81	36.8**	33.9**	7.1	4.2	23.5**	14.4**	22.7**	11.5**
HCN-113 x YD-4	-4.1**	-3.3**	-5.9**	-4.9**	23.6**	0.34	14.1**	-1.9**	3.5	-0.65	-5.9**	-8.2**	25.1**	23.6**
AML-113 x YD-4	-3.4**	-1.7*	-1.7*	0	-1.2	-5.9**	37.1**	16.6**	0.03	-3.1	16.3**	3.3	72.7**	68.9**
YD-01 x China-11	0	1.7*	2.5**	3.4**	30.1**	17.2**	-6.4*	-11.2**	0.14	-4.5	-1.6	-15.7**	15.9**	2.1
YD-2 x China-11	-1.7*	-1.7*	-0.27	0.64	51.8**	42.6**	4.1	2.6	-0.81	-2.1	5.4*	1.4	30.6**	29.4**
YL-1 x China-11	-2.5**	-1.7*	-4.1**	-1.6*	16.5**	4.7**	-5.1*	-9.2**	3.6	-2.9	2.8	-6.8**	5.6	4.2
YL-2 x China-11	-9.1**	-8.3**	-6.5**	-4.9**	27.5**	11.3**	16.1**	15.9**	7.6	1.1	21.2**	8.1**	34.1**	29.1**
YL-4 x China-11	-9.1**	-8.3**	-6.8**	-4.9**	34.7**	17.8**	25.3**	18.9**	2.6	-0.88	24.8**	16.8**	126.1**	120.6**
YL-5 x China-11	-0.83	0	1.4*	3.3**	12.5**	-2.2	13.1**	8.3**	-0.82	-4.1	9.2**	7.2**	31.1**	26.5**
YL-6 x China-11	0.87	5.5**	3.4**	7.1**	24.1**	12.7**	26.9**	18.5**	1.1	-4.9	-8.5**	-25.4**	136.8**	136.4**
YL-8 RC x China-11	-3.4**	-1.7*	0	1.7*	63.7**	56.4**	23.2**	8.3**	1.4	-5.7	36.6**	24.9**	61.8**	57.5**
HCN-113 x China-11	-5.8**	-5 **	-6.8**	-4.9**	44.6**	35.2**	-4.5	-8.8**	-7.1	-7.7	7.9**	6.9*	17.8**	10.9*
AML-113 x China-11	-1.7*	0	0.84	1.7*	14.4**	-5.7**	-3.3	-8.9**	-7.1	-8.7	-22.2**	-29.9**	33.3**	21.7**
YD-01 x YL-07 RC	5.9**	8.6**	4.9**	8.4**	5.6**	3.9**	-8.2**	-11.9**	-3.2	-8.1	-25.4**	-34.3**	-15.3**	-24.6**
YD-2 x YL-07 RC	5.8**	6.6**	6.4**	11.2**	36.6**	14.9**	1.5	-1.1	-7.8	-9.3	18.3**	10.4**	18.6**	16.1**
YL-1 x YL-07 RC	-9.8**	-9.8**	-8.9**	-3.4**	5.1**	3.8**	16.8**	12.9**	5.2	-1.8	24.8**	16.5**	149.9**	149.8**
YL-2 x YL-07 RC	-6.6**	-6.6**	-6.6**	-1.7*	13.3**	11.1**	15.7**	14.6**	1.1	-5.4	30.6**	19.9**	46.9**	43.1**
YL-4 x YL-07 RC	0	0	-1.1	4.5**	7.6**	5.7**	-1.7	-7.7**	-9.9	-13.3	26.7**	22.3**	22.5**	20.9**
YL-5 x YL-07 RC	-4.9**	-4.9**	-4.2**	1.1	19.6**	16.7**	-0.13	-3.3	2.3	-1.5	16.6**	15.1**	35.1**	31.8**
YL-6 x YL-07 RC	-1.7*	3.6**	-0.84	5.3**	13.1**	10.3**	30.1**	20.2**	2.1	-4.4	-16.2**	-30.1**	133.1**	130.7**
YL-8 RC x YL-07 RC	-5.9**	-3.5**	-3.6**	0.57	21.6**	3.9**	23.1**	7.2**	-12.4	-18.8	4.7	-6.9**	39.6**	34.3**
HCN-113 x YL-07 RC	-1.6*	-1.6*	-2.1**	3.4**	29.5**	8.5**	4.9	1.2	-11.1	-12.1	29.8**	26.9**	22.7**	16.9**
AML-113 x YL-07 RC	-0.84	1.7*	0	3.4**	2.3*	-6.1**	12.2**	6.9**	-4.9	-6.9	-12.7**	-19.1**	8.3*	-0.07

**, *: Significant at 1% and 5% probability levels, MPH= Mid-parent heterosis, BPH= Better-parent heterosis.

Table 5. Estimation of general combining ability effects for morphological, yield, and yield-related traits in yellow maize.

Lines	Days to anthesis	Days to silking	Plant height (cm)	Ear length (cm)	Ear diameter (cm)	100-grain weight (g)	Grain yield (kg ha^{-1})
YD-1	1.6*	2.1*	-7.3*	-1.2*	0.01	-0.69*	-593.4*
YD-2	1.60*	1.4*	-0.61	-1*	0.06	-1.8*	-1053.9*
YL-1	-0.07*	-0.58*	0.43	1.5*	0.08	1.3*	102.5
YL-2	-2.4*	-2.2*	9*	1.7*	0.07	4.6*	1041.9*
YL-4	0.27*	0.09	0.24	-1.1*	-0.11	2.7*	299.3*
YL-5	0.93*	1.3*	3.3*	-0.42*	0.06	-1.6*	-698.7*
YL-6	-0.07	0.31	-4.9*	1.6*	0.13	0.63*	2316.8*
YL-8 RC	-1.4*	-1.1*	1.1*	-0.80*	-0.12	-1.5*	-566.3*
HCN-113	-0.07	-1.2*	-4.4*	-1*	-0.10	-1.2*	-792.8*
AML-113	-0.40*	-0.02	3.1*	0.74*	-0.05	-2.4*	-55.4
SE line	0.05	0.26	0.53	0.18	0.10	0.19	74.4
Testers							
YD-4	0.10*	0.08	-0.71*	0.96*	-0.01	0.61*	464.2*
China-11	-0.70*	-0.79*	0.59*	-0.50*	0.06	-0.80*	-217.8*
YL-7 RC	0.60*	0.71*	0.12	-0.47*	-0.06	0.19*	-246.5*
SE tester	0.02	0.13	0.26	0.09	0.05	0.09	37.2

*: Significant at a 5% probability level.

Table 6. Estimation of specific combining ability effects for morphological, yield, and yield-related traits in yellow maize.

Crosses	Days to anthesis	Days to silking	Plant height (cm)	Ear length (cm)	Ear diameter (cm)	100-grain weight (g)	Grain yield (kg ha^{-1})
YD-01 x YD-4	-2.1*	-0.86	-7.3*	0.40	0.07	3.1*	957.6*
YD-2 x YD-4	-3.1*	-3.5*	-7.2*	-0.69*	0.04	-0.50	-569.4*
YL-1 x YD-4	2.6*	2.5*	21.7*	2.1*	-0.13	-1.2*	-1247.5*
YL-2 x YD-4	-0.10	0.14	6.7*	1.6*	-0.25	0.39	2265.7*
YL-4 x YD-4	1.2*	1.1*	-10.8*	-1.6*	-0.01	-0.34	-942.6*
YL-5 x YD-4	0.57*	0.59	1.1	-1.9*	-0.19	-2.4*	-499.6*
YL-6 x YD-4	1.6*	1.6*	-5.9*	0.20	0.15	2.3*	48.3
YL-8 RC x YD-4	0.90*	0.37	-2.7*	-0.98*	0.17	-0.67	-782.2*
HCN-113 x YD-4	-0.43*	-0.86	2.3*	-0.24	0.19	-3.7*	-174.3
AML-113 x YD-4	-1.1*	-1.1*	2.1*	1.1*	-0.04	3.1*	943.9*
YD-01 x China-11	-0.30*	-0.32	8.2*	-0.07	-0.12	0.98*	-63.2
YD-2 x China-11	-0.30*	-0.32	-0.48	0.42	0.09	-0.52	374.3*
YL-1 x China-11	1.4*	0.34	-11.4*	-2.8*	-0.03	-1.1*	-1438.5*
YL-2 x China-11	-0.30*	0.01	-3.1*	-0.54	0.18	-0.74*	-1415.8*
YL-4 x China-11	-2.9*	-2.3*	12.3*	2.9*	0.16	-0.26	1904.1*
YL-5 x China-11	1.4*	1.5*	-13.2*	2.1*	-0.01	0.67	157.1
YL-6 x China-11	0.37*	0.46	-0.59	-0.12	-0.21	0.13	45.5
YL-8 RC x China-11	0.70*	0.90	12.7*	0.62	0.07	2.9*	638.3*
HCN-113 x China-11	-0.63*	-0.99*	-4.2*	-0.39	-0.05	0.10	-62.8
AML-113 x China-11	0.70*	0.79	-0.33	-2.1*	-0.08	-2.2*	-138.9
YD-01 x YL-07 RC	2.4*	1.2*	-0.97	-0.33	0.05	-4.1*	-894.4*
YD-2 x YL-07 RC	3.4*	3.8*	7.7*	0.27	-0.13	1.1*	195.1
YL-1 x YL-07 RC	-3.9*	-2.8*	-10.3*	0.61	0.16	2.3*	2685.9*
YL-2 x YL-07 RC	0.40*	-0.16	-3.6*	-1.1*	0.07	0.35	-849.9*
YL-4 x YL-07 RC	1.7*	1.2*	-1.5*	-1.3*	-0.15	0.61	-961.4*
YL-5 x YL-07 RC	-1.9*	-2.1*	12.1*	-0.03	0.20	1.8*	342.6*
YL-6 x YL-07 RC	-1.9*	-2.1*	6.6*	-0.09	0.06	-2.4*	-93.8
YL-8 RC x YL-07 RC	-1.6*	-1.3*	-10.1*	0.36	-0.24	-2.2*	143.9
HCN-113 x YL-07 RC	1.1*	1.8*	1.9*	0.63	-0.13	3.6*	237.1
AML-113 x YL-07 RC	0.40*	0.29	-1.7	0.91*	0.12	-0.93*	-805.1*
SE	0.10	0.46	0.92	0.32	0.18	0.34	128.8

*: Significant at a 5% probability level.

values, which are desirable for early maturity. Regarding plant height, negative SCA estimates occurred for 13 F_1 crosses and can be effective for further breeding, as semi-dwarf maize plants are essential to avoid lodging. Aly *et al.* (2023) declared significant negative SCA estimates among the F_1 hybrids for days to anthesis and days to silking. The F_1 crosses with negative SCA effects for days to anthesis are beneficial and can serve in the development of early-maturing yellow maize hybrids (Belay, 2022). Six F_1 crosses showed significant and positive SCA effects for ear length. None of the F_1 crosses revealed notable SCA effects for ear diameter. The F_1 hybrids with significant positive SCA effects for ear length and ear diameter are highly desirable (Moneam *et al.,* 2015). Ten F_1 crosses resulted in having significant positive SCA values for 100-grain weight, and seven F_1 crosses revealed desirable positive SCA effects for grain yield ha^{-1}, which were analogous to results reported by Sedhom (2022).

Variance due to SCA was greater than GCA for all studied traits, indicating that a non-additive gene action played a vibrant role in controlling expression of all these traits. Most genetic variation associated with the studied traits resulted from a non-additive gene action. Higher SCA estimates for days to anthesis, days to silking, ear length, and grain yield ha^{-1} of yellow maize indicate the non-additive gene action was crucial in the inheritance of these traits (Shalof *et al.,* 2024).

CONCLUSIONS

Significant variability among the maize genotypes for all studied traits highlighted potential for selection. Based on the combining ability effects, the inbred lines YL-02 and YL-06 exhibited desirable and significant GCA values for earliness and yield-related traits, making them suitable for hybrid breeding. The F_1 hybrids, YL-01 × YL-07 RC, YL-02 × YD-04, and YL-04 × China-11, demonstrated significant SCA effects, having superior performance for yield and yield-related traits. These inbred lines and F_1 cross combinations can be suitable in future breeding programs for developing early-maturing and high-yielding maize hybrids.

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