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Genetic Analysis of Quantitative Traits in Maize: Evaluation of Diallel Crosses for Normal and Delayed Growth Using Various Stress Tolerance Indices

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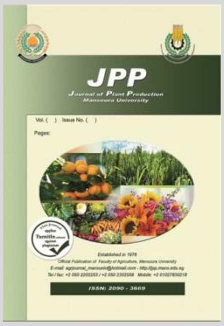

ABSTRACT

This study highlights the importance of general and specific combining abilities in maize breeding, emphasizing genotype-by-environment interactions. The findings revealed superior hybrids with enhanced stress tolerance, demonstrating the potential for developing high-yielding, resilient maize varieties adaptable to varying environmental conditions. Early sowing significantly improves vegetative growth and yield components, making it a key factor for enhanced maize production. Genetic variability among genotypes revealed substantial differences in performance, emphasizing the need for diverse parental lines in breeding programs. The study also found that non-additive genetic effects play a crucial role, highlighting the potential of hybrid breeding, especially through heterosis, to increase maize yield and stress tolerance. The hybrid $P_3 \times P_8$ demonstrated the highest heterotic effect (304.71%) relative to mid parent and superiority over SC 168 by 8.71, 19.29 and 13.64% at early, late planting dates and combined across them, respectively, making it the most promising candidate for commercial release. These findings suggest that multi-environment testing is necessary to identify stable hybrids across different planting conditions. Overall, the results indicate that P_3 and P_7 are promising parents for yield improvement due to their positive contributions to key agronomic traits. Genotypes P_3xP_8, P_1xP_3, P_2xP_7, P_6 and P_7, exhibited superior stress tolerance as evidenced by their higher STI, GMP, TOL, and YI values.

***Keywords**:* Maize, combining ability, planting date, stress tolerance indices, heterosis

INTRODUCTION

Maize (*Zea mays* L.), a globally significant crop, plays a crucial role in food security and as a raw material in various industries. Its extensive cultivation across diverse environmental conditions demands continual genetic improvements to ensure enhanced productivity, adaptability, and resilience. One of the key approaches in maize breeding involves hybrid development, which relies heavily on the evaluation of parental lines for their combining ability, a vital aspect for the selection of superior hybrid combinations (Hallauer *et al*., 2010).

Combining ability is generally divided into two primary categories: general combining ability (GCA) and specific combining ability (SCA). GCA refers to the average performance of an inbred line when crossed with other lines, driven largely by additive genetic effects. On the other hand, SCA reflects the hybrid vigor or specific performance of a particular cross and is predominantly influenced by non-additive genetic factors such as dominance and epistasis (Griffing, 1956). Both GCA and SCA are essential in maize hybrid breeding, with GCA providing insight into the overall genetic potential of the parental lines and SCA identifying specific combinations that show superior performance under particular conditions (Sprague and Tatum, 1942).

Understanding how GCA and SCA interact with environmental factors, especially over multiple planting dates, is critical in breeding programs. Environmental conditions such as temperature, precipitation, and soil characteristics can vary considerably from planting date to other, influencing the expression of both GCA and SCA. These genotype-by-environment interactions (GEI) can significantly affect hybrid performance, complicating the process of selecting stable, high-yielding hybrids (Yan and Kang, 2003). Therefore, assessing the stability and consistency of GCA and SCA across different planting dates enables breeders to identify hybrids that are not only high-performing but also resilient to environmental fluctuations (Crossa *et al*., 2004).

The estimation of stress tolerance indices in maize is an important tool in plant breeding programs, as it contributes to identifying genotypes that are more tolerant to adverse environmental conditions such as drought and heat. These indices, such as the Stress Tolerance Index (STI) and the Stress Susceptibility Index (SSI), help evaluate the performance of genotypes under stress conditions and compare it with their performance under normal conditions, thereby facilitating selection and improving production efficiency. Moreover, these indices contribute to understanding the relationship between physiological and yield traits, and they support the development of stable, high-yielding cultivars under climate change, enhancing food security and the sustainability of agricultural production.

This study aims to assess the general and specific combining abilities of maize inbred lines across multiple planting dates, examining how these genetic interactions are influenced by varying environmental conditions. Such an analysis is essential for improving the precision of hybrid selection and ensuring stable yields in diverse growing environments. Also, this study's primary goals were to

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determine combining ability, heterosis, superiority and the appropriate selection indices and assess promising genotypes for late planting date stress.

MATERIALS AND METHODS

This study was conducted using eight elite yellow maize inbred lines, each with varying yield potentials. These inbred lines included L 401 (P_1), L 1022 (P_2), L 4049 (P_3), L 235 (P_4), L 1040-R (P_5), L 1470 (P_6), L 422 (P_7), and L 200 (P_8). All these inbred lines were released over ten years ago from various local populations, except for L 1022 (P_2), which was imported from CIMMYT (CIMMYT Entry 195). The check hybrid used in the study was the single-cross hybrid Giza 168.

In the first season of 2023, 28 F_1 crosses were created from the eight parental inbred lines, excluding reciprocal crosses. These parental lines, F_1 crosses, and the check hybrid Giza 168 were evaluated in two separate experiments during the 2024 season at the Agricultural Research and Experimental Station, Faculty of Agriculture, Moshtohor, Egypt. The experiments were conducted with two different planting dates: May 2nd and June 15th. A randomized complete block design (RCBD) was used, with three replications for each planting date.

The climate conditions during the 2024 maize growing season in Kalubia Governorate, particularly in the Moshtohor region, were typical for maize cultivation. Average monthly temperatures ranged from 20.7°C in April to 31.9°C in July, with relative humidity fluctuating between 58% and 75% throughout the season. These warm temperatures and moderate humidity were conducive to maize growth. However, the rise in temperature, especially during late planting date, contributed to heat stress, and the plants were also affected by the response to the shorter day lengths typical of the season.

Each hybrid was planted on a ridge 6 meters long, with a plant density of 30 plants per ridge. The plant-to-plant spacing was 20 cm, and the ridge-to-ridge spacing was 70 cm. Initially, three kernels were planted per hill on one side of the ridge, and seedlings were later thinned to one plant per hill to achieve the optimal plant density. All other agronomic practices followed the standard recommendations for maize cultivation in the region.

A random sample of 15 representative plants was taken from each plot to evaluate several traits, including plant height (cm), ear height (cm), number of rows per ear, number of kernels per row, 100-kernel weight (g), and grain yield per plant (g), adjusted to 15.5% moisture content. Additionally, the days to 50% tasseling and silking were recorded when half of the plants had flowered. General and specific combining ability estimates were calculated using Griffing's (1956) diallel cross analysis, employing method 2 of model I. A combined analysis of both experiments was performed once homogeneity of variance was confirmed, as outlined by Gomez and Gomez (1984).

Heterosis percentages for grain yield per plant relative to the mid-parent (MP) and better-parent (BP) values were calculated according to Fonseca and Patterson (1968) as follows:

MP = [(F_1 value - mean of two parents) / (mean of two parents)] × 100

BP = [(F_1 value - value of best parent) / (value of best parent)] × 100

Superiority relative to the check hybrid Giza 168 was calculated as:

Superiority over Giza 168 = [(F_1 value - Giza 168 value) / (Giza 168 value)] × 100

Grain yield per plant under early (N) and late (L) planting conditions was analyzed for stress tolerance using several metrics, including geometric mean productivity (GMP) (Fernandez, 1992), harmonic mean (HM) (Bidinger and Mahalakshmi, 1987), tolerance index (TOL) (Roselle and Hamblin, 1981), yield index (YI) (Gavuzzi *et al.*, 1997), yield stability index (YSI) (Bouslama and Schapaugh, 1984), stress susceptibility index (SSI) (Fischer and Maurer, 1978), stress tolerance index (STI) (Fernandez, 1992), and relative stress index (RSI) (Bouslama and Schapaugh, 1984). Grain yield per plant for each genotype under late (Ys) and normal conditions (Yp) was used to compute the yield reduction ratio (YR) and yield index (YI), respectively. The mean yields for all genotypes under late and early planting conditions are denoted by_s and ʲp, respectively.

RESULTS AND DISCUSSION

The analysis of variance (ANOVA) revealed highly significant ($p < 0.01$) differences between the studied planting dates (E) (Table 1) with mean values in early planting date being higher than those in late sowing (Table 2). The observed increase in these traits at the early sowing date may be attributed to the favorable temperature and day length, which promote greater vegetative growth, yield, and its components in corn plants. Consequently, the first sowing date appears to represent a non-stress environment. These results are in harmony with those obtained by El-Bagoury *et al.* (2004), Amer (2005), El-Hosary and El-Badawy (2005), El-Hosary *et al*. (2006), Turk *et al.* (2020), Omar *et al.* (2022), Chen, *et al.*(2024) and Galal *et al.* (2025).

Genotypes (G) mean squares were significant for all traits in each and across planting dates (Table 1). This underscores the presence of substantial genetic variability, which is crucial for effective selection and breeding programs (Hallauer *et al.*, 2010). Moreover, the significance of genotype × planting date (G × D) interactions was observed for all studied traits. The differential response of genotypes to planting conditions suggests an interaction between genetic makeup and environmental factors, which necessitates multi-environment testing to ensure stable performance across different conditions (Yan and Holland 2010 and Badu-Apraku *et al*., 2012).

Significant parents' mean squares were obtained for all traits at both sowing dates as well as the combined analysis (Table 1). Insignificant interaction mean squares between parental inbred lines and planting dates were detected for all traits studied except No of rows / ear and 100-kernel weight Table (1). This result may reveal higher repeatability of performance of the parental inbred lines under different sowing dates. For the exceptional traits on the contrary, significant interaction was obtained revealing that the parental inbred lines varied in their response to sowing dates.

Crosses mean squares were significant for all traits revealing overall differences between these crosses. Significant interaction mean squares between hybrids and sowing dates were obtained for all traits Table (1), indicating the influence of both genetic and environmental factors on the measured traits. The mean performance values demonstrated variability in genotypic responses, which can be attributed to differential adaptability and genetic makeup. For the exceptional traits, insignificant interaction was obtained, reflecting that these crosses responded similarly to environmental changes.

The findings from this study have significant implications for maize breeding programs. The predominance of non-additive genetic effects for key agronomic traits suggests that hybrid breeding strategies will be more effective than pure-line selection. Additionally, the significant G × D interaction highlights the need for multi-environments trials to identify stable hybrids with broad adaptability. Future research should focus on dissecting the genetic basis of these interactions using molecular markers and genomic selection approaches.

Table 1. Mean squares for all the studied traits under early and late planting dates as well as the combined across them.

S.O.V.	Df	Days to 50% tasseling (day)	Days to 50% silking (day)	Plant height (cm)	Ear height (cm)	number of rows/ ear	number of kernels/ row	100-kernel weight (g)	Grain yield/ plant (g)
				Early planting date					
Rep	2	11.12**	2.23*	1606.75**	466.68**	3.65**	0.42	1.01	18.49
Genotypes (G)	35	31.43**	27.66**	8150.88**	1518.45**	8.52**	142.20**	72.97**	7128.04**
Parent (P)	7	2.09**	4.57**	518.38**	56.80**	13.69**	129.37**	40.13**	951.82**
Cross (C)	27	38.56**	33.61**	1257.10**	344.50**	5.16**	28.66**	35.69**	2338.31**
P vs C.	1	44.37**	28.61**	247710.72**	43446.45**	62.88**	3297.55**	1309.49**	179684.54**
Error	70	0.4	0.65	2.09	0.94	0.34	1.43	3.68	6.99
				Late planting date					
Rep	2	9.25**	3.37*	1606.75**	468.75**	1.25**	23.26**	4.85	13.18
Genotypes (G)	35	33.02**	34.60**	7598.88**	1170.29**	9.13**	174.81**	77.73**	6005.76**
Parent (P)	7	3.47**	8.29**	258.38**	129.23**	13.88**	52.68**	57.02**	898.89**
Cross (C)	27	40.72**	38.55**	913.57**	543.46**	5.60**	38.25**	48.62**	1942.82**
P vs C.	1	31.72**	112.26**	239486.01**	25382.29**	71.27**	4716.99**	1008.78**	151453.31**
Error	70	0.7	0.71	2.09	0.96	0.23	1.63	2.12	5.68
				Combined analysis					
planting date (D)	1	453.56**	450.67**	14701.50**	22346.34**	26.13**	660.85**	514.28**	44845.07**
Rep/D	4	10.19**	2.80**	1606.75**	467.71**	2.45**	11.84**	2.93	15.84*
Genotypes (G)	35	62.01**	57.66**	15165.24**	2594.17**	17.18**	299.12**	144.85**	12749.15**
Parent (P)	7	4.24**	8.19**	712.46**	124.75**	27.28**	150.63**	94.10**	1753.09**
Cross (C)	27	76.49**	67.91**	1430.89**	825.94**	10.24**	54.20**	77.87**	3830.14**
P vs C.	1	75.56**	127.12**	487162.01**	67622.35**	134.02**	7951.19**	2308.47**	330535.03**
G x D	35	2.44**	4.61**	584.53**	94.57**	0.47*	17.90**	5.86**	384.65**
p xD	7	1.32*	4.67**	64.29**	61.29**	0.3	31.43**	3.05	97.62**
C xD	27	2.80**	4.26**	739.77**	62.02**	0.53*	12.71**	6.44**	450.99**
P.vs.C x D	1	0.53	13.76**	34.71**	1206.38**	0.13	63.35**	9.79	602.81**
Error	140	0.55	0.68	2.09	0.95	0.29	1.53	2.9	6.33

*** and ** significant at 0.05 and 0.01 levels of probability, respectively.**

The means performance of the tested eight inbred lines and the tested 28 hybrids at each planting date and as an average over the planting dates are present in Table (2).

For tasseling date, the inbred lines no. 1, 2 and 3 at early sowing date, no. 2 and 4 at late planting date and the combined across planting date gave the lowest values of this trait. However, parental combinations that incorporated earliness in tasseling dates are plants of F_1 crosses 1x2, 1x6, 2x6, 3x5, 3x7, 5x6, and 6x7 at early planting date, 1x7, 5x6, and 5x7 at late planting date and the combined analysis.

As for days to 50% to silking date, the inbred line no. 3 in early sowing date and combined analysis, no. 4 in late sowing date, behaved as the earliest inbred lines. However, the crosses 1x7, 1x8, 2x3, 3x8, 5x6 and 5x7 at early planting date, 1x7, 5x6, and 5x7 at late planting date and 1x3, 1x8, 3x4, 3x8 and 5x7 at the combined analysis exhibited the earliest crosses.

Early crosses like, 1x3, 1x7, 3x8 and 5x7 are important for improving adaptability, yield stability, and resilience to environmental conditions as well as escape a biotic stress. They help ensure efficient use of short growing seasons, and enable double cropping. These hybrids require fewer inputs, enhance yield stability, and support climate change adaptation. Additionally, they offer economic benefits by allowing early harvests before market saturation.

The choice between taller or short plants with reduced ear height depends on the breeder's objective.

The parental inbred line no.2 and the cross 3x8 gave the highest mean values for plant height in both and across planting dates. However, the parental inbred lines no. 3 and 5 as well as the cross 3x6 had the lowest mean values for ear height. Selecting tall maize plants with reduced ear height improves lodging resistance, enhances biomass production, optimizes light interception, and ensures better nutrient allocation. It also facilitates harvesting and enhances drought and heat tolerance, leading to higher yield stability and efficiency. But, selecting short maize plants like, 2x3 and 2x8 enhances harvest efficiency, increases stress tolerance, optimizes energy allocation for grain production, and allows higher planting density for greater yield potential.

The parental inbred line no. 4 and the cross 2x7 had the highest mean values for number of rows/ ear.

The parental inbred lines no. 6 and 7 as well as the cross 5x7 gave the highest mean value for number of kernels/ row in both and across planting dates.

The parental inbred line no. 6 and the cross 3x8 gave the highest mean values for 100-kernel weight and grain yield/ plant in both and across planting dates.

Superior maize hybrids play a vital role in enhancing yield potential, stress tolerance, nutrient efficiency, and grain quality. They exhibit hybrid vigor (heterosis), leading to higher productivity and better adaptability under various environmental conditions. Hybrids also offer earliness, uniformity, and improved resistance to pests, diseases, and abiotic stresses such as drought and heat. Their efficient nutrient use reduces input costs, while their economic benefits outweigh the higher seed cost, making them ideal for commercial farming. Overall, superior maize hybrids contribute significantly to food security, profitability, and sustainable agriculture.

Table 2. Mean performance of all genotypes for all studied traits at two planting dates and their combined data.

Genotypes	Days to 50% tasseling (day)			Days to 50% silking (day)			plant height (cm)			Ear height (cm)		
	E	L	Com.	E	L	Com.	E	L	Com.	E	L	Com.
1x1	57.67	53.67	55.67	55.33	50.33	52.83	195.33	175.33	185.33	107.00	97.00	102.00
2x2	55.67	52.00	53.83	54.33	50.33	52.33	210.67	185.67	198.17	111.67	111.67	111.67
3x3	55.67	53.67	54.67	53.33	50.67	52.00	180.33	170.33	175.33	101.33	91.33	96.33
4x4	56.33	52.67	54.50	54.67	49.67	52.17	180.33	170.33	175.33	112.33	92.33	102.33
5x5	56.67	54.33	55.50	54.67	52.33	53.50	170.33	165.33	167.83	102.67	92.67	97.67
6x6	57.33	54.67	56.00	55.33	52.33	53.83	175.67	160.67	168.17	113.00	93.00	103.00
7x7	57.67	53.33	55.50	57.33	50.33	53.83	175.33	155.33	165.33	107.00	97.00	102.00
8x8	57.33	55.33	56.33	56.33	54.67	55.50	180.33	165.33	172.83	108.67	96.67	102.67
1x2	55.33	50.67	53.00	56.67	51.33	54.00	310.67	310.67	310.67	176.33	151.33	163.83
1x3	50.33	48.33	49.33	52.33	50.00	51.17	315.67	300.67	308.17	172.67	152.67	162.67
1x4	57.33	53.67	55.50	56.33	53.00	54.67	310.67	290.67	300.67	163.33	148.00	155.67
1x5	58.33	55.67	57.00	60.67	59.33	60.00	310.33	285.33	297.83	151.67	126.67	139.17
1x6	51.67	50.67	51.17	54.67	52.67	53.67	315.67	300.67	308.17	162.00	137.00	149.50
1x7	50.33	46.67	48.50	52.67	49.67	51.17	300.33	285.33	292.83	153.00	123.00	138.00
1x8	51.33	49.33	50.33	52.33	49.67	51.00	310.67	300.67	305.67	162.67	142.67	152.67
2x3	50.67	48.33	49.50	53.67	49.33	51.50	370.33	250.33	310.33	151.67	126.67	139.17
2x4	60.33	57.33	58.83	61.67	57.33	59.50	300.33	274.33	287.33	151.33	131.33	141.33
2x5	55.67	54.33	55.00	56.33	54.67	55.50	290.33	260.33	275.33	141.67	116.67	129.17
2x6	53.33	51.67	52.50	52.67	54.33	53.50	310.33	295.33	302.83	171.67	141.67	156.67
2x7	57.33	55.33	56.33	56.67	54.67	55.67	300.33	300.33	300.33	172.00	152.00	162.00
2x8	60.67	59.33	60.00	61.33	59.67	60.50	270.67	250.67	260.67	151.33	111.33	131.33
3x4	50.33	49.67	50.00	51.33	50.33	50.83	300.33	290.33	295.33	156.67	141.67	149.17
3x5	54.33	52.33	53.33	54.33	51.67	53.00	290.67	280.67	285.67	162.33	142.33	152.33
3x6	59.67	57.67	58.67	60.33	59.67	60.00	270.33	260.33	265.33	132.67	112.67	122.67
3x7	55.33	51.67	53.50	55.33	53.67	54.50	290.67	260.67	275.67	163.00	133.00	148.00
3x8	50.33	47.33	48.83	50.67	49.67	50.17	330.33	310.33	320.33	162.00	142.00	152.00
4x5	56.33	54.67	55.50	57.33	56.67	57.00	280.67	270.67	275.67	161.67	141.67	151.67
4x6	60.67	55.67	58.17	60.67	59.67	60.17	290.67	280.67	285.67	162.67	147.67	155.17
4x7	59.33	55.33	57.33	59.67	55.33	57.50	280.67	275.67	278.17	157.33	132.33	144.83
4x8	58.33	53.67	56.00	59.33	55.33	57.33	280.67	270.67	275.67	141.67	111.67	126.67
5x6	52.33	46.33	49.33	54.67	49.33	52.00	280.67	275.67	278.17	142.00	122.00	132.00
5x7	50.67	45.67	48.17	53.33	48.33	50.83	300.67	300.67	300.67	158.00	148.00	153.00
5x8	58.33	54.67	56.50	59.67	55.33	57.50	300.67	295.67	298.17	152.67	132.67	142.67
6x7	54.33	51.67	53.00	55.67	51.67	53.67	290.33	260.33	275.33	141.67	111.67	126.67
6x8	57.67	55.33	56.50	59.67	56.33	58.00	280.33	280.33	280.33	146.67	116.67	131.67
7x8	56.33	54.33	55.33	59.33	57.33	58.33	280.67	272.67	276.67	151.33	136.33	143.83
SC 168	60.10	56.20	58.15	58.40	55.20	56.80	273.10	255.7	264.4	160.67	147.67	154.17
L.S.D 5%	1.02	1.36	1.18	1.31	1.37	1.32	2.35	2.35	2.32	1.58	1.59	1.56
L.S.D 1%	1.36	1.80	1.55	1.74	1.82	1.73	3.12	3.12	3.04	2.09	2.11	2.05

Table 2. Cont.

Genotypes	No of rows / ear			No of Kernels/ row			100-kernel weight (g)			Grain weight/ plant (g)		
	E	L	Com.	E	L	Com.	E	L	Com.	E	L	Com.
1x1	9.25	9.09	9.17	22.70	17.34	20.02	28.33	23.77	26.05	54.84	39.43	47.14
2x2	12.70	12.00	12.35	22.37	18.63	20.50	29.11	28.60	28.86	76.13	50.33	63.23
3x3	13.53	13.00	13.26	22.68	20.43	21.56	23.67	20.60	22.13	64.20	47.30	55.75
4x4	14.76	13.55	14.16	19.61	17.65	18.63	25.67	22.10	23.88	67.00	42.60	54.80
5x5	11.03	9.90	10.47	28.76	19.00	23.88	21.67	19.60	20.64	63.90	40.77	52.34
6x6	10.48	9.00	9.74	32.69	29.84	31.27	33.33	32.60	32.97	95.37	85.36	90.37
7x7	15.12	14.60	14.86	38.67	23.67	31.17	24.67	22.10	23.38	108.00	74.00	91.00
8x8	10.85	10.27	10.56	22.33	19.05	20.69	25.33	24.10	24.72	72.57	41.67	57.12
1x2	13.17	12.55	12.86	36.95	25.67	31.31	27.17	24.93	26.05	121.33	180.33	160.83
1x3	15.37	14.13	14.75	40.17	36.30	38.23	35.67	34.10	34.88	189.53	177.00	183.27
1x4	15.60	15.22	15.41	43.46	41.40	42.43	34.17	27.60	30.88	205.53	159.70	182.62
1x5	12.13	10.65	11.39	40.64	31.00	35.82	37.50	33.27	35.39	170.33	140.11	155.22
1x6	13.10	12.50	12.80	42.30	37.32	39.81	33.50	29.60	31.55	169.00	124.90	146.95
1x7	14.77	13.20	13.98	36.74	34.94	35.84	26.83	22.10	24.47	131.63	121.00	126.32
1x8	12.80	11.95	12.38	37.27	36.53	36.90	37.33	32.60	34.97	156.13	140.67	148.40
2x3	13.63	13.57	13.60	37.04	37.09	37.06	39.67	36.60	38.13	179.00	164.70	171.85
2x4	14.70	13.24	13.97	38.52	36.60	37.56	34.83	33.60	34.22	176.67	149.97	163.32
2x5	13.20	12.83	13.02	39.12	37.83	38.48	36.50	33.10	34.80	166.01	154.67	160.34
2x6	14.00	13.30	13.65	42.07	38.87	40.47	33.67	32.60	33.13	185.73	148.03	166.88
2x7	16.40	16.37	16.39	42.92	33.88	38.40	35.83	29.60	32.72	223.00	141.67	182.33
2x8	13.52	12.50	13.01	38.31	34.74	36.53	37.00	33.10	35.05	170.67	119.52	145.09
3x4	14.91	13.70	14.31	42.11	40.17	41.14	29.67	27.10	28.38	162.44	134.00	148.22
3x5	13.60	13.63	13.62	39.83	38.50	39.16	34.83	28.60	31.72	169.03	149.00	159.02
3x6	14.40	14.17	14.29	38.15	37.40	37.78	37.33	36.10	36.72	186.93	153.35	170.14
3x7	15.55	15.50	15.52	38.10	34.84	36.47	30.17	29.10	29.63	158.30	138.76	148.53
3x8	15.38	15.10	15.24	39.61	39.38	39.49	43.25	41.10	42.18	236.33	226.00	231.17
4x5	13.63	11.80	12.72	40.82	40.06	40.44	32.83	30.10	31.47	160.67	135.33	148.00
4x6	16.12	14.15	15.14	43.44	38.67	41.05	36.00	34.60	35.30	228.33	167.33	197.83
4x7	15.50	14.93	15.22	36.51	33.00	34.76	34.83	31.60	33.22	181.33	133.27	157.30
4x8	13.00	12.80	12.90	37.03	34.15	35.59	35.50	34.10	34.80	147.73	126.00	136.87
5x6	12.50	12.30	12.40	35.63	35.67	35.65	35.33	33.60	34.47	138.40	123.40	130.90
5x7	13.66	13.62	13.64	47.78	43.38	45.58	33.67	24.60	29.13	206.33	155.00	180.67
5x8	11.06	10.50	10.78	41.14	40.69	40.91	37.17	30.60	33.88	144.07	116.77	130.42
6x7	13.85	13.57	13.71	35.79	35.07	35.43	32.83	30.43	31.63	148.00	122.76	135.38
6x8	12.60	12.50	12.55	41.77	38.90	40.33	37.33	35.10	36.22	173.33	158.00	165.67
7x8	15.23	14.37	14.80	33.28	32.72	33.00	35.33	33.43	34.38	168.33	136.00	152.17
SC 168	14.00	13.42	13.71	43.2	40.00	41.6	40.5	38.8	39.56	217.40	189.45	203.43
L.S.D 5%	0.95	0.78	0.85	1.94	2.08	1.98	3.12	2.36	2.72	4.29	3.87	4.03
L.S.D 1%	1.25	1.03	1.12	2.57	2.75	2.60	4.13	3.14	3.57	5.69	5.13	5.28

Differences between parental lines (P) and their corresponding crosses (C) for all traits, as evidenced by the P vs. C mean squares, confirm the presence of heterosis (Table 1). Particularly, the large variance observed in grain yield-related traits such as ear weight per plant (EWP) and grain weight per plant (GWP) suggests that hybrids outperform their parental lines, a well-documented phenomenon in maize breeding (Duvick, 2005). The significant P vs. C × D interaction for several traits further indicates that hybrid superiority is influenced by planting date, reinforcing the importance of optimizing planting conditions for maximum genetic gain.

Heterosis, or hybrid vigor, is a crucial factor in hybrid maize breeding. In this study, significant heterosis was observed for most crosses, demonstrating their potential for enhancing yield and other agronomic traits.

The highest heterosis relative to the mid-parent (Table 3) was observed in cross 3×8 (309.62%), followed by 1×3 (256.24%) and 1×4 (258.29%) in the combined across planting dates, indicating substantial genetic divergence and potential for hybrid development.

Regarding heterosis relative to the better parent (Table 3), the highest values were again recorded in 3×8 (304.71%), followed by 1×3 (228.74%) and 1×4 (233.25%). These hybrids exhibited remarkable heterotic effects, suggesting strong complementation of parental alleles. In contrast, crosses such as 6×7, 1×7, and 5×6 exhibited relatively lower heterosis values, which may indicate limited genetic divergence between parents or the presence of recessive deleterious alleles.

One of the primary objectives of hybrid breeding is to develop new hybrids that outperform existing commercial checks. The superiority of hybrids over SC 168 was evaluated (Table 3), and the results were as follows:

The cross 3×8 exhibited the highest superiority over SC 168, with positive gains i.e. 8.71%, 19.29%, 13.64% at early, late planting date and a combined across them, respectively. This suggests that this hybrid has the potential to outperform the commercial check under varying environmental conditions. Similarly, 4×6 showed a positive superiority i.e. 5.03% at early planting date, indicating its adaptability and potential yield improvement.

However, most crosses exhibited negative values, meaning they performed below SC 168. This could be attributed to non-optimal parental combinations, genotype-environment interactions, or the strong performance of SC 168 itself.

The most inferior crosses included 1×2, 1×6, and 5×8, which showed significant yield reductions compared to the check, suggesting that these hybrids may not be suitable for commercial production.

The hybrid 3×8 demonstrated the best overall performance, with the highest heterosis and positive superiority over SC 168. It should be considered a promising candidate for further evaluation and possible commercial release. Other hybrids, such as 4×6, also showed potential but need further validation. Future breeding programs should focus on combining high heterotic effects with superior yield stability across different environments.

Table 3. Heterosis relative to mid, better parent and superiority over SC 168 for grain yield/ plan at both early and late planting dates and combined data across them.

cross	Mid-parent			better parent			Superiority% over check hybrid SC 168		
	E	L	Comb	E	L	Comb	E	L	Comb
1x2	85.28**	78.99**	82.71**	59.37**	59.61**	59.47**	-44.19**	-4.81*	-50.43**
1x3	218.43**	308.16**	256.24**	195.22**	274.21**	228.74**	-12.82**	-6.57**	-9.91**
1x4	237.38**	289.37**	258.29**	206.76**	274.88**	233.25**	-5.46**	-15.7**	-10.23**
1x5	186.9**	249.4**	212.06**	166.56**	243.66**	196.56**	-21.65**	-26.04**	-23.7**
1x6	125.02**	100.18**	113.73**	77.2**	46.32**	62.61**	-22.26**	-34.07**	-27.76**
1x7	61.67**	113.35**	82.89**	21.88**	63.51**	38.81**	-39.45**	-36.13**	-37.9**
1x8	145.08**	246.91**	184.67**	115.14**	237.58**	159.8**	-28.18**	-25.75**	-27.05**
2x3	155.11**	237.4**	188.87**	135.12**	227.24**	171.79**	-17.66**	-13.06**	-15.52**
2x4	146.87**	222.76**	176.74**	132.06**	197.97**	158.3**	-18.74**	-20.84**	-19.71**
2x5	137.11**	239.56**	177.48**	118.06**	207.31**	153.58**	-23.64**	-18.36**	-21.18**
2x6	116.59**	118.19**	117.29**	94.75**	73.42**	84.66**	-14.57**	-21.86**	-17.96**
2x7	142.22**	127.89**	136.44**	106.48**	91.45**	100.36**	2.58	-25.22**	-10.37**
2x8	129.55**	159.83**	141.11**	124.18**	137.47**	129.46**	-21.49**	-36.91**	-28.68**
3x4	147.62**	198.11**	168.15**	142.45**	183.3**	165.87**	-25.28**	-29.27**	-27.14**
3x5	163.9**	238.37**	194.24**	163.29**	215.01**	185.24**	-22.25**	-21.35**	-21.83**
3x6	134.29**	131.19**	132.88**	96.01**	79.65**	88.27**	-14.02**	-19.06**	-16.36**
3x7	83.86**	128.79**	102.43**	46.57**	87.51**	63.22**	-27.18**	-26.76**	-26.99**
3x8	245.59**	408.04**	309.62**	225.66**	377.8**	304.71**	8.71**	19.29**	13.64**
4x5	145.49**	224.65**	176.27**	139.81**	217.68**	170.07**	-26.09**	-28.57**	-27.25**
4x6	181.25**	161.53**	172.55**	139.41**	96.03**	118.91**	5.03*	-11.68**	-2.75*
4x7	107.23**	128.59**	115.78**	67.9**	80.09**	72.86**	-16.59**	-29.65**	-22.67**
4x8	111.69**	199.04**	144.59**	103.57**	195.77**	139.62**	-32.05**	-33.49**	-32.72**
5x6	73.79**	95.67**	83.45**	45.12**	44.56**	44.85**	-36.34**	-34.86**	-35.65**
5x7	140.06**	170.11**	152.09**	91.05**	109.46**	98.54**	-5.09**	-18.18**	-11.19**
5x8	111.14**	183.28**	138.3**	98.53**	180.23**	128.33**	-33.73**	-38.36**	-35.89**
6x7	45.55**	54.07**	49.29**	37.04**	43.81**	48.77**	-31.92**	-35.2**	-33.45**
6x8	106.42**	148.76**	124.65**	81.74**	85.1**	83.32**	-20.27**	-16.6**	-18.56**
7x8	86.44**	135.15**	105.47**	55.86**	83.78**	67.22**	-22.57**	-28.21**	-25.2**

*** and ** significant at 0.05 and 0.01 levels of probability, respectively.**

General and Specific Combining Ability

The mean squares for general combining ability (GCA) and specific combining ability (SCA) were significant for all studied traits in both and across planting dates (Table 4), indicating the importance of both additive and non-additive genetic effects (Sprague and Tatum, 1942). The higher magnitude of SCA mean squares compared to GCA for all studied traits except, number of days to 50% tasseling at early planting date, and days to 50% silking at early planting date and combined analysis, number of rows/ ear in both and across planting date suggests a predominant role of non-additive gene action, particularly for ear height (EH) and grain weight per plant (GWP). This pattern is consistent with previous studies that highlighted the significance of dominance and epistatic effects in maize diallel crosses (Reid *et al*., 2014).

Moreover, The GCA/SCA ratio varied across traits, with values less than 1.0 for plant height (PH) and ear height (EH), indicating a dominance of non-additive genetic effects.

Conversely, traits such as the number of rows per ear (NRE) and 100-kernel weight (100KW) exhibited GCA/SCA ratios greater than 1.0, suggesting the preeminence of additive gene action (Falconer and Mackay 1996). These findings emphasize the importance of selecting superior parents for hybrid development while considering heterosis exploitation. The genetic variance was previously reported to be mostly due to non-additive for plant and ear heights by Shafey *et al.* (2003), El-Hosary and El-Badawy (2005); El-Shenawy (2005) and El-Hosary *et al.* (2006). On the other hand, the additive genetic variance was previously reported to be the most prevalent for earliness by El-Shenawy (2005) and El-Hosary *et al.* (2006); no. of rows/ear by El-Hosary and El-Badawy (2005), El-Shenawy (2005); 100-kernel weight by Shafey *et al.* (2003), El-Hosary and El-Badawy (2005), Turk, *et al.* (2020) and Galal *et al.* (2025).

Notably, the GCA × D and SCA × D interactions were significant for all studied traits except no of rows/ ear but of lower magnitude compared to the main effects, indicating that both additive and non-additive effects are influenced by environmental conditions, albeit to a lesser extent.

For all studied traits, the ratio of SCA x D/SCA was lower than GCA x D/GCA. This result indicated that additive effects were more influenced by planting date than non-additive genetic effects for this trait. This conclusion is in well agreement with those reported by Gilbert (1958).

Table 4. Combining ability mean squares for earliness traits, plant height, ear height, yield and its components under early and late planting dates as well as the combined data across them.

S.O.V.	Df	days to 50% tasseling (day)	days to 50% silking (day)	Plant height (cm)	Ear height (cm)	number of rows/ ear	number of kernels/ row	100-kernel weight (g)	Grain yield/ plant (g)
				Early planting date					
GCA	7	10.67**	10.44**	677.26**	78.17**	8.11**	18.80**	14.97**	437.63**
SCA	28	10.43**	8.91**	3226.89**	613.14**	1.52**	54.55**	26.66**	2860.61**
Error	70	0.13	0.22	0.7	0.31	0.11	0.48	1.23	2.33
GCA/SCA		1.02	1.17	0.21	0.13	5.34	0.34	0.56	0.15
				Late planting date					
GCA	7	8.88**	10.64**	242.09**	110.15**	8.64**	19.00**	35.58**	473.13**
SCA	28	11.54**	11.76**	3105.68**	460.08**	1.64**	68.09**	23.49**	2384.12**
Error	70	0.23	0.24	0.7	0.32	0.08	0.54	0.71	1.89
GCA/SCA		0.77	0.90	0.08	0.24	5.27	0.28	1.51	0.20
				Combined analysis					
GCA	7	18.79**	19.55**	718.69**	176.11**	16.57**	28.28**	47.44**	758.83**
SCA	28	21.14**	19.13**	6139.18**	1036.88**	3.02**	117.56**	48.49**	5122.44**
GCA x L	7	0.76**	1.53**	200.66**	12.22**	0.18	9.52**	3.11**	151.93**
SCA x L	28	0.83**	1.54**	193.39**	36.35**	0.15	5.08**	1.66*	122.29**
Error	140	0.18	0.23	0.7	0.32	0.1	0.51	0.97	2.11
GCA/SCA		0.89	1.02	0.12	0.17	5.49	0.24	0.98	0.15
GCA x L/GCA		0.04	0.08	0.28	0.07	0.01	0.34	0.07	0.2
SCA x L/SCA		0.04	0.08	0.03	0.04	0.05	0.04	0.03	0.02

*** p< 0.05; ** p< 0.01**

General combining ability (GCA) effects

The analysis of general combining ability (GCA) effects $\hat{g}_i$ for various agronomic traits in maize under two planting dates and their combined analysis (Table 5) provided valuable insights into the genetic contributions of different parental lines.

The GCA effects for tasseling and silking dates revealed significant differences among the parental lines. Notably, parents P_1 and P_3 exhibited highly significant negative GCA effects for tasseling (-1.11**) and silking (-1.08**) dates, indicating their potential contribution to early flowering genotypes. Early flowering is a desirable trait as it enhances escape from terminal drought stress and heat stress, which is critical in maize productivity (Badu-Apraku *et al*., 2020). Conversely, P_4 displayed significant positive GCA effects (1.30** for tasseling and 0.92** for silking), suggesting its contribution to late-maturing genotypes, which could be beneficial in environments with a long growing season (Menkir *et al*., 2018).

Significant positive GCA effects for plant height were observed in $\mathbf{P_1}$ (11.07** cm) and $\mathbf{P_2}$ (5.98** cm), suggesting their potential for increasing plant stature. Taller plants generally contribute to higher biomass and could be advantageous for silage maize (Kamara *et al*., 2014). However, P_6 (-5.18**) and P_7 (-5.37**) showed negative effects, indicating their suitability for developing shorter genotypes, which are often preferred for lodging resistance. For ear height, similar trends were observed, with $\mathbf{P_1}$ contributing significantly (4.77**), whereas P_6 (-3.75**) had the lowest values. Lower ear height is advantageous in reducing lodging risk, improving mechanical harvesting efficiency (Fasahat *et al*., 2016).

The GCA effects for yield components demonstrated considerable genetic variability among the parental lines. The number of rows per ear and kernels per row are critical determinants of final grain yield. P_3 and P_7 recorded the highest positive GCA effects for the number of rows per ear (0.82** and 1.33**, respectively), whereas P_5 exhibited the most negative GCA effects (-1.12**). For kernels per row, P_6 and P_5 showed significant positive effects (1.97** and 1.05**), indicating their potential in enhancing kernel number, a crucial yield component (Adebayo *et al*., 2022). Conversely, P_1 (-1.30**) had significantly negative effects, suggesting its limited contribution to this trait.

A similar trend was observed for 100-kernel weight, where $\mathbf{P_6}$ (2.20**) and P_8 (1.79**) exhibited superior performance for GCA effects. The grain yield per plant, a direct measure of yield potential, was highest in $\mathbf{P_3}$ (8.93**), reaffirming its strong yield potential. In contrast, P_1 (-9.65**) and $\mathbf{P_5}$ (-6.51**) exhibited significantly negative GCA effects, suggesting a reduced ability to contribute to higher yields.

Overall, the results indicate that P_3 and P_7 are promising parents for yield improvement due to their positive contributions to key agronomic traits. In contrast, P_1 and P_5 displayed negative effects for most traits, suggesting their limited utility in yield improvement programs. These findings align with previous research highlighting the importance of parental selection in maize breeding (Hallauer *et al*., 2010). Future breeding efforts should focus on incorporating high GCA-effect parents into hybrid development programs to enhance maize productivity and adaptability under different planting conditions.

Table 5. Estimates of general combining ability effects for all studied traits at the combined analysis.

Parent	days to 50% tasseling (day)	days to 50% silking (day)	Plant height (cm)	Ear height (cm)	number of rows/ ear	number of kernels/ row	100-kernel weight (g)	Grain yield / plant (g)
P1	-1.11**	-1.08**	11.07**	4.77**	-0.77**	-1.30**	-1.27**	-9.65**
P2	0.55**	0.27**	5.98**	2.90**	0.16**	-1.25**	0.88**	-1.72**
P3	-1.48**	-1.70**	2.75**	0.09	0.82**	-0.09	0.29*	8.93**
P4	1.30**	0.92**	-3.48**	1.14**	0.83**	-0.31**	-0.70**	0.94**
P5	-0.15**	0.07	-3.68**	-2.25**	-1.12**	1.05**	-1.09**	-6.51**
P6	0.40**	0.65**	-5.18**	-3.75**	-0.56**	1.97**	2.20**	6.01**
P7	-0.41**	-0.28**	-5.37**	0.25**	1.33**	0.85**	-2.10**	3.03**
P8	0.89**	1.17**	-2.08**	-3.16**	-0.69**	-0.92**	1.79**	-1.03**
L.S.D(0.05) gi	0.10	0.11	0.19	0.13	0.07	0.16	0.23	0.34
L.S.D(0.01) gi	0.13	0.14	0.25	0.17	0.09	0.22	0.30	0.44
L.S.D(0.05) gi-gj	0.19	0.21	0.37	0.25	0.14	0.31	0.43	0.64
L.S.D(0.01) gi-gj	0.25	0.27	0.48	0.32	0.18	0.41	0.56	0.83

*** p< 0.05; ** p< 0.01**

Specific combining ability (SCA) effects

Specific combining ability effects ŝij for the F_1 crosses for the studied traits in the combined analysis are presented in (Table 6).

For days to 50% tasseling and days to 50% silking, twelve and ten crosses expressed significant and significant ŝij effects, respectively. Moreover, the cross P3xP8, P5 x P6 and P5 x P7 gave the most desirable ŝij effects for earliness traits. However, three cross combinations i.e. P_1xP_5, P_3xP_6, P_4xP_6 and P_4xP_7 gave significant and positive ŝij effects for the above mention traits. For plant height, all crosses except P_2xP_8 in the combined analysis expressed significant and positive ŝij effects. Moreover, the cross P_3xP_8 gave the most desirable ŝij effects for this trait. For ear height, six crosses expressed significant and negative ŝij effects. However, the best ŝij effects (-8.99**) were detected for the cross P_3xP_6.

Table 6. Estimates of specific combining ability effects for yield and its components 'at the combined analysis.

cross combinations	days to 50% tassling (day)	days to 50% silking (day)	Plant height (cm)	Ear height (cm)	number of rows/ ear	number of kernels/ row	100-kernel weight (g)	Grain yield/ plant (g)
P1xP2	-0.59*	0.13	28.73**	20.85**	0.19	-0.96*	-5.00**	-24.95**
P1xP3	-2.22**	-0.74*	29.46**	22.50**	1.41**	4.80**	4.42**	46.83**
P1xP4	1.16**	0.15	28.19**	14.45**	2.06**	9.22**	1.41*	54.17**
P1xP5	4.11**	6.33**	25.56**	1.33**	-0.01	1.25**	6.30**	34.23**
P1xP6	-2.27**	-0.59	37.39**	13.16**	0.84**	4.32**	-0.82	13.43**
P1xP7	-4.12**	-2.15**	22.24**	-2.34**	0.13	1.48**	-3.60**	-4.22**
P1xP8	-3.59**	-3.77**	31.79**	15.75**	0.54**	4.30**	3.00**	21.93**
P2xP3	-3.72**	-1.75**	36.71**	0.86*	-0.67**	3.59**	5.52**	27.49**
P2xP4	2.83**	3.63**	19.94**	1.98**	-0.31	4.31**	2.59**	26.95**
P2xP5	0.45	0.48	8.14**	-6.80**	0.68**	3.87**	3.56**	31.43**
P2xP6	-2.60**	-2.10**	37.14**	22.20**	0.76**	4.93**	-1.39*	25.44**
P2xP7	2.05**	1.00**	34.83**	23.53**	1.60**	3.99**	2.50**	43.87**
P2xP8	4.41**	4.38**	-8.12**	-3.72**	0.25	3.88**	0.93	10.70**
P3xP4	-3.97**	-3.07**	31.18**	12.63**	-0.64**	6.72**	-2.66**	1.19
P3xP5	0.81**	-0.05	21.71**	19.18**	0.62**	3.39**	1.07	19.45**
P3xP6	5.60**	6.36**	2.88**	-8.99**	0.74**	1.08*	2.79**	18.04**
P3xP7	1.25**	1.80**	13.39**	12.35**	0.08	0.9	0	-0.59
P3xP8	-4.72**	-3.99**	54.78**	19.76**	1.81**	5.69**	8.65**	86.12**
P4xP5	0.2	1.33**	17.94**	17.46**	-0.29	4.89**	1.81**	16.42**
P4xP6	2.31**	3.91**	29.44**	22.46**	1.57**	4.58**	2.36**	53.73**
P4xP7	2.30**	2.18**	22.13**	8.13**	-0.24	-0.6	4.57**	16.18**
P4xP8	-0.34	0.56	16.34**	-6.62**	-0.54**	2.00**	2.26**	-0.19
P5xP6	-5.07**	-3.40**	22.14**	2.68**	0.78**	-2.18**	1.91**	-5.75**
P5xP7	-5.42**	-3.64**	44.83**	19.68**	0.13	8.87**	0.88	46.99**
P5xP8	1.61**	1.58**	39.04**	12.76**	-0.71**	5.97**	1.74**	0.81
P6xP7	-1.14**	-1.39**	20.99**	-5.15**	-0.36	-2.21**	0.1	-10.82**
P6xP8	1.06**	1.50**	22.71**	3.26**	0.51*	4.47**	0.79	23.54**
P7xP8	0.71**	2.76**	19.23**	11.43**	0.86**	-1.74**	3.25**	13.02**
LSD5%(sij)	0.54	0.6	1.05	0.71	0.39	0.9	1.24	1.83
LSD1%(sij)	0.7	0.79	1.38	0.93	0.51	1.18	1.62	2.39
LSD5%(sij-sik)	0.79	0.89	1.55	1.05	0.57	1.33	1.83	2.7
LSD1%(sij-sik)	1.04	1.16	2.04	1.37	0.75	1.74	2.4	3.54
LSD5%(sij-skL)	0.26	0.3	0.52	0.35	0.19	0.44	0.61	0.9
LSD1%(sij-skL)	0.35	0.39	0.68	0.46	0.25	0.58	0.8	1.18

*** p< 0.05; ** p< 0.01**

Regarding to number of rows/ ear, fourteen cross combinations expressed significant and positive ŝij effects. The cross P_1xP_4 being the highest one in this traits and recorded 2.06**. Twenty one crosses combinations exhibited significant and positive ŝij effects for no of kernels/ row. The best positive ŝij effects were the crosses P_1 x P_4 and P_5xP_7 in the combined analysis (Table 6).

For 100-kernel weight, seventeen crosses showed significant and positive ŝij effects for no of kernels/ row. The best positive ŝij effects were the crosses P_1xP_5 and P_5xP_7 in the combined analysis (Table 6). Regarding to grain yield/ plant twenty one crosses exhibited significant and positive ŝij effects However, the cross P_3xP_8 exhibited significant and positive ŝij effects and ranked the number one.

The results indicate that several crosses exhibited significant SCA effects for key agronomic traits, emphasizing their potential in hybrid breeding programs. Notably, $P_3×P_8$ emerged as the most promising hybrid for enhancing both plant growth and grain yield. Additionally, crosses such as $P_5×P_7$, $P_1×P_4$, and $P_3×P_6$ showed desirable SCA effects for specific traits, making them valuable candidates for future maize improvement efforts. These findings highlight the importance of hybrid selection in maximizing genetic gains for yield and its related traits under varying planting conditions.

The evaluation of 36 maize genotypes for grain yield per plant under normal (Yp) and stress (Ys) conditions using various stress tolerance indices revealed significant variability in stress tolerance across the genotypes.

Performance under Normal and Stress Conditions

The mean grain yield per plant under normal conditions (Yp) ranged from 236.33 g (P_3xP_8) to 54.84 g (P_1), with a grand mean of 151.56 g. Under stress conditions (Ys), the yield reduction was evident, with values ranging from 226 g (P_3xP_8) to 39.43 g (P_1), yielding a mean of 122.74 g. This substantial reduction in yield under stress conditions suggests varying levels of stress tolerance among the genotypes.

Stress Tolerance Indices (STI)

The Stress Tolerance Index (STI) varied between 2.33 (3x8) and 0.09 (P_1). Higher STI values indicated better stress tolerance, with hybrids like 3x8, P6, and P_7 showing strong tolerance. P_1 exhibited the lowest STI, indicating lower stress resilience. These results suggest that hybrid combinations, such as 3x8 and P_7, are more adapted to stress environments, displaying higher yield stability under both normal and stress conditions.

Heterosis and Performance Relative to Parents

Hybrid combinations, especially those such as 1x3 and 3x8, displayed remarkable yield increases compared to their parents. For instance, 3x8 showed a yield of 226.00 g under stress, demonstrating its potential as a high-performance cross. On the other hand, parental lines like P_1 showed smaller yield increases, reflecting their inherent limitations in stress tolerance. Geometric Mean Productivity (GMP): This index showed the best performance for genotypes like P_6 and 3x8, which maintained relatively high yield performance under both conditions. The mean GMP value of 136.15 g suggests that some hybrids can combine yield stability and stress tolerance effectively. Tolerance (TOL) and Stress Susceptibility Index (SSI): The TOL values for some hybrids, like P_7 and 2x7, were relatively high, indicating their ability to tolerate stress to a certain extent. However, hybrids like P_6 had lower tolerance, further confirming their sensitivity to stress conditions. Similarly, the SSI values indicated that genotypes with higher SSI, such as P1, are more susceptible to stress, while hybrids like 1x3 exhibited lower SSI, signifying higher stress resilience.

Table 7. Mean values of delay tolerance indices for grain yield/ plant under normal and stress late dates for 36 tested maize genotypes.

Genotypes	Yp	Ys	STI	MP	GMP	HARM	TOL	SSI	YI	YSI	SDI	RDI
P1	54.84	39.43	0.09	47.14	46.50	45.88	15.41	1.48	0.32	0.72	0.28	0.89
P2	76.13	50.33	0.17	63.23	61.90	60.60	25.80	1.78	0.41	0.66	0.34	0.82
P3	64.20	47.30	0.13	55.75	55.11	54.47	16.90	1.38	0.39	0.74	0.26	0.91
P4	67.00	42.60	0.12	54.80	53.42	52.08	24.40	1.92	0.35	0.64	0.36	0.79
P5	63.90	40.77	0.11	52.34	51.04	49.78	23.13	1.90	0.33	0.64	0.36	0.79
P6	95.37	85.36	0.35	90.37	90.23	90.09	10.01	0.55	0.70	0.90	0.10	1.11
P7	108.00	74.00	0.35	91.00	89.40	87.82	34.00	1.66	0.60	0.69	0.31	0.85
P8	72.57	41.67	0.13	57.12	54.99	52.94	30.90	2.24	0.34	0.57	0.43	0.71
1x2	121.33	80.33	0.42	100.83	98.72	96.66	41.00	1.78	0.65	0.66	0.34	0.82
1x3	189.53	177.00	1.46	183.27	183.16	183.05	12.53	0.35	1.44	0.93	0.07	1.15
1x4	205.53	159.70	1.43	182.62	181.17	179.74	45.83	1.17	1.30	0.78	0.22	0.96
1x5	170.33	140.11	1.04	155.22	154.48	153.75	30.22	0.93	1.14	0.82	0.18	1.02
1x6	169.00	124.90	0.92	146.95	145.29	143.64	44.10	1.37	1.02	0.74	0.26	0.91
1x7	131.63	121.00	0.69	126.32	126.20	126.09	10.63	0.42	0.99	0.92	0.08	1.14
1x8	156.13	140.67	0.96	148.40	148.20	148.00	15.46	0.52	1.15	0.90	0.10	1.11
2x3	179.00	164.70	1.28	171.85	171.70	171.55	14.30	0.42	1.34	0.92	0.08	1.14
2x4	176.67	149.97	1.15	163.32	162.77	162.23	26.70	0.79	1.22	0.85	0.15	1.05
2x5	166.01	154.67	1.12	160.34	160.24	160.14	11.34	0.36	1.26	0.93	0.07	1.15
2x6	185.73	148.03	1.20	166.88	165.81	164.75	37.70	1.07	1.21	0.80	0.20	0.98
2x7	223.00	141.67	1.38	182.34	177.74	173.27	81.33	1.92	1.15	0.64	0.36	0.78
2x8	170.67	119.52	0.89	145.10	142.82	140.59	51.15	1.58	0.97	0.70	0.30	0.86
3x4	162.44	134.00	0.95	148.22	147.54	146.86	28.44	0.92	1.09	0.82	0.18	1.02
3x5	169.03	149.00	1.10	159.02	158.70	158.38	20.03	0.62	1.21	0.88	0.12	1.09
3x6	186.93	153.35	1.25	170.14	169.31	168.48	33.58	0.94	1.25	0.82	0.18	1.01
3x7	158.30	138.76	0.96	148.53	148.21	147.89	19.54	0.65	1.13	0.88	0.12	1.08
3x8	236.33	226.00	2.33	231.17	231.11	231.05	10.33	0.23	1.84	0.96	0.04	1.18
4x5	160.67	135.33	0.95	148.00	147.46	146.92	25.34	0.83	1.10	0.84	0.16	1.04
4x6	228.33	167.33	1.66	197.83	195.46	193.13	61.00	1.41	1.36	0.73	0.27	0.90
4x7	181.33	133.27	1.05	157.30	155.45	153.63	48.06	1.39	1.09	0.73	0.27	0.91
4x8	147.73	126.00	0.81	136.87	136.43	136.00	21.73	0.77	1.03	0.85	0.15	1.05
5x6	138.40	123.40	0.74	130.90	130.68	130.47	15.00	0.57	1.01	0.89	0.11	1.10
5x7	206.33	155.00	1.39	180.67	178.83	177.02	51.33	1.31	1.26	0.75	0.25	0.93
5x8	144.07	116.77	0.73	130.42	129.70	128.99	27.30	1.00	0.95	0.81	0.19	1.00
6x7	148.00	122.76	0.79	135.38	134.79	134.20	25.24	0.90	1.00	0.83	0.17	1.02
6x8	173.33	158.00	1.19	165.67	165.49	165.31	15.33	0.47	1.29	0.91	0.09	1.13
7x8	168.33	136.00	1.00	152.17	151.30	150.45	32.33	1.01	1.11	0.81	0.19	1.00
Mean	151.56	122.74	0.90	137.15	136.15	135.16	28.82	1.07	1.00	0.80	0.20	0.98

Yield Index (YI) and Yield Stability Index (YSI): These indices helped identify the most stable hybrids across both normal and stress conditions. For example, 3x8 and 1x3 exhibited high YI and YSI, suggesting they are not only high-yielding but also stable in varying environmental conditions.

The analysis revealed significant differences in stress tolerance among the 36 maize genotypes, with certain hybrids, especially 3x8, 1x3, 2x7, P_6 and P_7, exhibiting superior stress tolerance as evidenced by their higher STI, GMP, TOL, and YI values. These genotypes not only exhibited higher grain yields under normal conditions but also maintained relatively good performance under stress, making them promising candidates for further breeding programs aimed at enhancing maize resilience to stress. The use of multiple stress tolerance indices allowed a comprehensive evaluation of the genotypes, helping to identify those most suited for stress-prone environments.

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التحليل الوراثي للصفات الكمية في الذرة: تقييم التهجينات التبادلية للنمو العادي و المتأخر باستخدام مؤشرات مختلفة لتحمل الإجهاد

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الملخص

تُبرز هذه الدراسة أهمية القدرة العامة والخاصة على الائتلاف في تحسين الذرة، مع التركيز على تفاعل الجينات مع البيئة. أظهرت النتائج وجود هجن متفوقة بقدرة محسنة على تحمل الإجهاد، مما يعكس إمكانات تطوير أصناف ذرة عالية الإنتاجية وقادرة على التأقلم مع الظروف البيئية المتغيرة. كما تبين أن الزراعة المبكرة تؤثر إيجابياً على النمو الخضري ومكونات المحصول، مما يجعلها عاملًا أساسيًا في تحسين إنتاجية الذرة. كشفت الدراسة عن تباين وراثي كبير بين التراكيب الوراثية، مما يؤكد أهمية استخدام آباء متنوعة في برامج التربية. كما أظهرت النتائج أن التأثيرات الوراثية غير الإضافية تلعب دورًا رئيسيًا، مما يشير إلى أهمية التربية لانتاج الهجن، وخاصة من خلال ظاهرة قوة الهجين (Heterosis) ، لزيادة إنتاجية الذرة وتحسين تحملها للإجهاد. حقق الهجين $P_3 \times P_8$ أعلى قوة هجين بنسبة 304.71٪ بالنسبة لمتوسط الأبوين، كما تفوق على الصنف التجاري SC 168 بنسبة 8.71٪، 19.29٪، و13.64٪ عند مواعيد الزراعة المبكرة والمتأخرة وعند متوسطهما، مما يجعله المرشح الأكثر واعدًا للإطلاق التجاري. تؤكد هذه النتائج أهمية اختبارات البيئات المتعددة لتحديد الهجن الأكثر استقرارًا تحت مواعيد زراعية مختلفة بشكل عام. أظهرت النتائج أن P_3 وP_7 يمثلان آباء واعدة لتحسين الإنتاجية، نظرًا لمساهمتهما الإيجابية في الصفات الزراعية الأساسية. كما برهنت التراكيب الوراثية $P_3 \times P_8$، $P_1 \times P_3$، $P_2 \times P_7$، P_6، وP_7 على تفوقها في تحمل الإجهاد، استنادًا إلى قيمها المرتفعة لمؤشرات STI وGMP وTOL وYI .