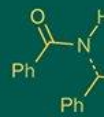


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(6): 1133-1138
www.biochemjournal.com
Received: 23-04-2026
Accepted: 27-05-2026

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Line × Tester analysis for combining ability and yield it's traits in maize (*Zea mays* L.)

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6Sn.8775>

Abstract

The present investigation was conducted to assess combining ability and gene action for yield and its contributing traits in maize (*Zea mays* L.) using a Line × Tester design. Eight inbred lines obtained from NBPGR, New Delhi were crossed with three testers to produce 24 hybrids. The experimental material was evaluated during *Kharif* 2023-2024 in a randomized block design. Analysis of variance revealed significant differences among genotypes for all the traits, indicating ample genetic variability. Combining ability analysis showed significant GCA and SCA effects for most characters. The predominance of non-additive gene action for yield traits was indicated by higher SCA variance, degree of dominance greater than unity, and low predictability ratio, suggesting the effectiveness of heterosis breeding. Among parents, IC 296599 and IC 405281 were identified as superior general combiners for grain yield and related traits, while IC 405284 and IC 569176 were suitable for earliness. Among testers, Jawahar showed favourable effects for yield, whereas PC-4 contributed to early maturity. Cross combinations such as IC 296599 × PC-4, IC 405281 × Narmada Moti, and IC 569176 × Jawahar exhibited high SCA effects and heterosis. The higher magnitude of SCA in F_1 compared to F_2 indicated partial loss of dominance due to segregation. The study highlights the importance of both additive and non-additive gene action and identifies promising parental lines and hybrids for maize improvement.

Keywords: Maize, line × tester, combining ability, GCA, SCA, heterosis, gene action

Introduction

Maize (*Zea mays* L.; $2n = 2x = 20$) is one of the most important cereal crops worldwide, known for its wide adaptability, high productivity, and diverse uses. As a C_4 plant, it exhibits high photosynthetic efficiency and biomass production, enabling successful cultivation across tropical and temperate regions. Due to its utilization as food, feed, fodder, and industrial rawmaterial, maize is often referred to as the “queen of cereals” and plays a vital role in global agriculture.

Globally, maize is cultivated on around 200 million hectares and contributes significantly to food security, livestock production, and industrial sectors. The demand for maize continues to rise due to population growth, increasing consumption of animal products, and expanding industrial uses such as starch and biofuel production. Recent projections indicate steady growth in global production and consumption, emphasizing its economic and strategic importance. In India, maize ranks third after rice and wheat and is grown across diverse agro-climatic conditions. Its production has increased in recent years due to the adoption of improved hybrids and better agronomic practices. However, productivity remains relatively low during the *Kharif* season due to erratic rainfall, moisture stress, and biotic constraints. In contrast, Rabi and Zaid maize generally show higher productivity under more favourable growing conditions. In states like Uttar Pradesh, maize is cultivated across multiple seasons and contributes significantly to the cropping system, although its yield potential remains underexploited in many regions. Maize originated in Central America and was domesticated thousands of years ago before spreading worldwide. It is a highly cross-pollinated crop, resulting in considerable genetic variability and heterozygosity. While this enhances its adaptability, it also leads to inbreeding depression, making hybrid breeding essential for achieving higher productivity. The exploitation of heterosis has been a major breakthrough in maize improvement, leading to the development of high-yielding hybrids.

Combining ability analysis, particularly general combining ability (GCA) and specific combining ability (SCA), is a valuable tool in maize breeding. GCA reflects additive gene

effects, while SCA represents non-additive gene action, including dominance and epistasis. Understanding the relative importance of these genetic components helps breeders select superior parents and identify promising hybrid combinations. Traits governed by additive gene action can be improved through selection, whereas those controlled by non-additive effects are better exploited through hybrid breeding.

With the increasing demand for maize in food, feed, and industrial sectors, including its growing role in biofuel production, there is a need to enhance yield potential and stability. Climate change, resource limitations, and biotic stresses pose additional challenges to maize production. Therefore, the development of high-yielding, early-maturing, and stress-tolerant hybrids has become a major objective of maize breeding programmes. In this context, the present study was undertaken to evaluate the combining ability of maize inbred lines using a Line $\times$ Tester mating design. The objective was to identify superior parental lines and cross combinations for yield and its contributing traits, and to understand the nature of gene action governing these characters for effective crop improvement.

Materials and methods

Experimental site: The study was conducted at the Agricultural Research Farm of S. M. M. Town Post Graduate College, Ballia, Uttar Pradesh, India, during *Kharif* 2022, *Zaid* 2023, and *Kharif* 2023-2024. The experimental site lies in the middle Gangetic plains (25°33'–26°11' N latitude and 83°38'–84°39' E longitude) at an altitude of about 59 m above mean sea level. The region has a subtropical climate with hot summers and cool winters. The average annual temperature is around 25°C, with rainfall of approximately 648 mm, mostly received during the monsoon season. The soil is alluvial and suitable for maize cultivation.

Plant material and mating design

The experimental material comprised eight maize inbred lines (IC series) L1(IC 405284) L2(IC 569176) L3(IC 408327) L4(IC 405280) L5(IC 563954) L6(IC 584593) L7(IC 296599) L8(IC 405281) and three testers obtained from NBPGR, New Delhi. The lines represented diverse genetic backgrounds with variation in maturity, yield potential, and stress tolerance. The testers (PC-4, Jawahar, and Narmada Moti) were selected based on their agronomic performance.

Crosses were made using a Line $\times$ Tester mating design (Kempthorne, 1957) ^[10], where eight lines were crossed with three testers to produce 24 F₁ hybrids. Hybridization was carried out during *Kharif* 2022 using standard hand-pollination techniques, ensuring controlled crossing and genetic purity.

Development and evaluation of generations

During *Zaid* 2023, F₁ plants were selfed to produce F₂ seeds, and fresh crosses were also made to maintain F₁ seed. In *Kharif* 2023-2024, the F₁ hybrids, F₂ populations, parental lines, and three standard check varieties were evaluated in the field.

The experiment was laid out in a Randomized Block Design (RBD) with three replications. Each entry was grown in three rows of 4 m length, maintaining a spacing of 60 cm between rows and 25 cm between plants. Standard

agronomic practices were followed uniformly, and thinning was done to maintain one healthy plant per hill.

Data collection: Observations were recorded on five randomly selected plants per plot, while phenological traits were recorded on a plot basis. The traits studied included days to 50% tasseling, days to 50% silking, plant height, ear height, number of leaves per plant, cob length, number of ears per plant, kernel rows per ear, days to maturity, biological yield per plant, grain yield per plant, thousand kernel weight, harvest index, and protein content. Harvest index was calculated as the ratio of grain yield to total biological yield and expressed in percentage. Protein content was estimated using the standard Kjeldahl method.

Statistical analysis: Combining ability analysis was conducted using the Line $\times$ Tester mating design as proposed by Oscar Kempthorne (1957) ^[10] and further refined by V. Arunachalam (1974) ^[11] to assess the genetic control of quantitative traits in maize. This method partitioned the total genetic variance into general combining ability (GCA) and specific combining ability (SCA), representing additive and non-additive gene effects, respectively. The statistical model was applied, and analysis of variance was performed following R. A. Fisher (1935) ^[16]. Variance components were estimated using mean squares, where GCA and SCA variances were derived to determine the relative importance of gene action. The interpretation of results was based on the ratio of GCA to SCA variances, as suggested by H. F. Robinson *et al.* (1949) ^[16], enabling identification of superior parents and cross combinations for maize improvement.

Results and discussion

Combining ability analysis (ANOVA)

The analysis of variance for combining ability revealed that mean squares due to crosses, lines, testers, and line $\times$ tester interactions were highly significant for all the characters in both F₁ and F₂ generations. This indicated the presence of substantial genetic variability among the parental lines and hybrids, and confirmed the effectiveness of the Line $\times$ Tester design in partitioning genetic components.

Significant line and tester effects suggested the importance of general combining ability (GCA), reflecting additive gene action governing the inheritance of traits. Simultaneously, the significant line $\times$ tester interactions indicated the presence of specific combining ability (SCA), which is associated with non-additive gene action such as dominance and epistasis. The significance of both GCA and SCA in F₁ and F₂ generations demonstrated the involvement of both additive and non-additive genetic components, offering scope for both selection and hybrid breeding. These findings are in agreement with earlier reports of Sprague and Tatum (1942) and Moll *et al.* (1962) ^[13].

General Combining Ability (GCA) Effects

The estimation of GCA effects revealed considerable variability among parental lines for all traits. Lines IC 296599 and IC 405281 emerged as superior general combiners for grain yield and most yield-contributing traits, exhibiting significant positive effects across both generations. Their consistent performance indicates the predominance of additive gene action and their suitability as reliable donors in breeding programmes.

Table 1: Combining ability ANOVA for parents and hybrids (F₁)

Source of variation	DF	Day to tassel emergence (days)	Days to silking (days)	Plant height (cm)	No. of leaves per plant	Ear height (cm)	Cob length (cm)	No. of kernel rows per ear	No. of ears per plant	Days to maturity (days)	Biological yield per plant (g)	Harvest index (%)	1000 kernel weight(g)	Protein content (%)	Grain yield per plant (g)
REPLN	2	1.00	1.09	3.40	2.277	18.67	0.005	0.163	0.001	12.94	10.60	1.25	1.53	0.008	0.53
CROSS	23	19.66**	19.37**	350.17**	1.791**	186.05**	2.428**	2.273**	0.333**	154.49**	3743.81**	34.92**	3593.23**	2.039**	848.36**
LINE(c)	7	41.41**	41.33**	658.74**	2.213**	359.28**	3.389**	4.678**	1.038**	288.40**	5706.24**	26.98**	6704.10**	2.477**	1746.38**
TEST(c)	2	18.07**	18.93**	317.26**	0.442**	127.81**	2.656**	1.641**	0.005**	343.55**	2479.14**	31.84**	494.22**	0.136**	153.53**
LXT (c)	14	9.01**	8.44**	200.58**	1.772**	107.76**	1.914**	1.161**	0.027**	60.53**	2943.26**	39.33**	2480.51**	2.092**	498.62**
ERROR	46	0.28	0.27	6.70	0.168	7.13	0.400	0.468	0.001	3.95	20.55	1.87	15.24	0.041	10.07
TOTAL	71	6.57	6.48	117.78	0.751	65.32	1.040	1.038	0.109	52.91	1226.10	12.53	1173.71	0.686	281.22

Table 2: Combining ability ANOVA for parents and F₂

Source of variation	DF	Day to tassel emergence (days)	Days to silking (days)	Plant height (cm)	No. of leaves per plant	Ear height (cm)	Cob length (cm)	No. of kernel rows per ear	No. of ears per plant	Days to maturity (days)	Biological yield per plant (g)	Harvest index (%)	1000 kernel weight(g)	Protein content (%)	Grain yield per plant (g)
REPLN	2	1.69	1.60	4.46	2.167	7.63	0.168	0.860	0.001	4.86	17.19	3.12	1.99	0.112	4.69
CROSS	23	27.90**	23.16**	620.47**	1.747**	340.77**	4.336**	1.362**	0.095**	147.04**	4615.94**	54.09**	1916.99**	0.977**	822.31**
LINE(c)	7	26.56**	29.71**	899.91**	2.232**	536.98**	5.325**	2.802**	0.258**	361.31**	5847.10**	39.89**	2955.55**	0.977**	1054.31**
TEST(c)	2	39.83**	31.27**	891.22**	1.322**	430.90**	9.491**	2.180**	0.007**	218.32**	800.89**	52.62**	462.48**	1.604**	792.25**
LXT (c)	14	26.87**	18.72**	442.07**	1.565**	229.79**	3.106**	0.525**	0.026**	29.72**	4545.36**	61.40**	1605.50**	0.888**	710.60**
ERROR	46	1.20	1.13	8.23	0.211	6.81	0.288	0.126	0.001	0.56	18.97	1.24	18.62	0.140	6.45
TOTAL	71	9.85	8.26	206.34	0.760	114.92	1.592	0.545	0.032	48.12	1507.81	18.39	632.85	0.409	270.60

*, ** significant at 5% and 1% level, of significance respectively

For earliness traits, IC 405284 and IC 569176 showed significant negative GCA effects for days to tasseling, silking, and maturity, identifying them as desirable parents for developing early-maturing hybrids. In contrast, IC 563954 exhibited positive GCA effects, indicating late maturity.

Traits such as plant height, ear height, cob length, kernel rows per ear, number of ears per plant, biological yield, and 1000-kernel weight were predominantly governed by additive gene action, as indicated by stable and significant

GCA effects across generations. The consistency of these effects suggests that selection in early segregating generations would be effective for their improvement.

Moderate variability in GCA effects was observed for traits like number of leaves per plant, harvest index, and protein content, indicating the involvement of both additive and non-additive gene action. Among testers, Jawahar exhibited favourable GCA effects for yield-related traits, whereas PC-4 contributed to earliness, highlighting the importance of tester selection.

Table 3: GCA effects of parents in F₁ and F₂ generation in (*Zea mays* L.)

SN.	Parents/ Hybrids	Day to tassel emergence (days)		Days to silking (days)		Plant Height (cm)		No. of leaves per plant		Ear height (cm)		Cob length (cm)		No. of kernel rows / ear	
	Lines	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂
1	IC 405284	-2.42 **	-2.38 **	-2.46 **	-2.37 **	10.28 **	2.07 *	0.48 **	-0.02	7.00 **	5.82 **	0.17	-1.00 **	0.06	-0.49 **
2	IC 569176	-2.82 **	-0.49	-2.83 **	-0.43	-2.17 *	-3.47 **	-0.46 **	0.15	-1.79 *	1.84 *	-0.44 *	0.67 **	-0.74 **	0.11
3	IC 408327	-0.75 **	-0.71	-0.71 **	-1.74 **	-6.56 **	-10.61 **	0.17	-0.40 *	-2.77 **	-12.37 **	-0.73 **	0.26	0.46 *	-0.47 **
4	IC 405280	-0.06	0.54	-0.02	0.61	-8.33 **	-5.60 **	-0.54 **	-0.58 **	-4.17 **	-5.82 **	0.41	-0.46 *	0.41	-0.49 **
5	IC 563954	2.12 **	0.61	2.12 **	0.68	-2.83 **	-2.36 *	-0.39 **	-0.54 **	-4.73 **	-4.10 **	0.09	-1.00 **	-1.13 **	-0.51 **
6	IC 584593	-0.15	3.00 **	-0.04	3.10 **	-8.10 **	-9.67 **	-0.34 *	0.04	-8.27 **	-3.42 **	-0.88 **	-0.13	-0.54 *	0.46 **
7	IC 296599	0.45 *	-1.78 **	0.34	-1.31 **	3.42 **	13.98 **	0.32 *	0.60 **	8.53 **	8.01 **	0.69 **	0.75 **	0.57 *	0.62 **
8	IC405281	3.63 **	1.20 **	3.60 **	1.46 **	14.29 **	15.66 **	0.77 **	0.75 **	6.22 **	10.05 **	0.67 **	0.91 **	0.90 **	0.78 **
	Testers														
9	PC -4	-0.92 **	-1.33 **	-0.91 **	-1.17 **	-4.15 **	6.77 **	-0.16	0.26 **	2.64 **	4.66 **	-0.11	0.08	0.10	-0.03
10	Jawahar	0.11	1.24 **	0.04	1.11 **	2.60 **	-1.74 **	0.06	-0.06	-1.63 **	-3.62 **	0.37 **	0.58 **	0.20	0.32 **
11	Narmada moti	0.81 **	0.09	0.87 **	0.07	1.55 **	-5.03 **	0.09	-0.20 *	-1.01	-1.04	-0.26 *	-0.67 **	-0.30 *	-0.28 **
	SE(gca for l)	0.174	0.361	0.172	0.351	0.854	0.946	0.135	0.151	0.881	0.860	0.209	0.177	0.226	0.117
	SE(gca for t)	0.107	0.221	0.105	0.215	0.523	0.579	0.083	0.093	0.539	0.527	0.128	0.108	0.138	0.072
	SE(bet gca of l)	0.246	0.511	0.243	0.496	1.207	1.338	0.191	0.214	1.245	1.217	0.295	0.250	0.319	0.166
	SE(bet gca of t)	0.151	0.313	0.149	0.304	0.739	0.819	0.117	0.131	0.763	0.745	0.181	0.153	0.195	0.101

Table 4: GCA effects of parents in F₁ and F₂ generation in (*Zea mays* L.)

SN	Parents/ Hybrids	No. of ears / plants		Days to maturity (days)		Biological yield / Plant (g)		Harvest index (%)		1000 kernel weight(g)		Protein content (%)		Grain yield per plant (g)	
		F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂
1	IC 405284	-0.35 **	-0.15 **	-5.55 **	-9.81 **	8.59 **	-10.90 **	-1.99 **	0.44	-4.94 **	-20.29 **	-0.48 **	-0.04	0.12	-4.02 **
2	IC 569176	-0.30 **	-0.14 **	-6.06 **	-3.59 **	-2.19	-9.58 **	-0.32	3.16 **	9.27 **	0.54	1.12 **	-0.20	-1.44	3.44 **
3	IC 408327	-0.19 **	-0.19 **	3.45 **	3.23 **	-11.81 **	-29.69 **	1.40 **	0.44	-0.55	-18.55 **	-0.30 **	-0.60 **	-2.15 *	-10.89 **
4	IC 405280	-0.23 **	-0.08 **	-6.93 **	-5.86 **	-25.43 **	-6.16 **	1.81 **	-0.84 *	-34.97 **	8.11 **	-0.19 **	-0.03	-8.16 **	-4.01 **
5	IC 563954	-0.02	0.03 **	7.81 **	9.14 **	-17.49 **	-8.45 **	0.27	-2.95 **	-1.10	10.58 **	-0.37 **	0.34 **	-7.42 **	-9.15 **
6	IC 584593	0.10 **	0.07 **	5.90 **	6.14 **	-22.59 **	-12.92 **	-3.10 **	-0.80 *	-35.49 **	-22.16 **	-0.04	0.49 **	-19.91 **	-7.03 **
7	IC 296599	0.39 **	0.18 **	0.32	-1.28 **	24.46 **	47.81 **	0.71	-2.01 **	46.59 **	19.96 **	-0.13	-0.01	13.38 **	12.43 **
8	IC405281	0.59 **	0.28 **	1.05	2.03 **	46.47 **	29.89 **	1.21 **	2.57 **	21.20 **	21.81 **	0.38 **	0.04	25.58 **	19.23 **
	Testers														
9	PC -4	-0.01	-0.01	-2.52 **	-2.04 **	-3.64 **	5.83 **	0.99 **	0.21	-2.86 **	-5.07 **	0.08	-0.15	0.87	3.23 **
10	Jawahar	0.01 *	0.02 *	4.35 **	3.46 **	11.48 **	-0.10	-1.26 **	1.36 **	5.23 **	2.45 **	-0.07	-0.15	1.98 **	3.40 **
11	Narmada moti	0.000	-0.010	-1.83 **	-1.42 **	-7.85 **	-5.72 **	0.27	-1.58 **	-2.37 **	2.62 **	-0.01	0.30 **	-2.85 **	-6.63 **
	SE(gca for l)	0.012	0.012	0.655	0.246	1.494	1.436	0.451	0.367	1.287	1.423	0.067	0.124	1.046	0.838
	SE(gca for t)	0.007	0.007	0.401	0.151	0.915	0.879	0.276	0.225	0.788	0.871	0.041	0.076	0.641	0.513
	SE(bet gca of l)	0.017	0.017	0.927	0.348	2.113	2.031	0.638	0.519	1.820	2.012	0.094	0.175	1.479	1.185
	SE(bet gca of t)	0.010	0.010	0.567	0.213	1.294	1.244	0.391	0.318	1.115	1.232	0.058	0.107	0.906	0.725

*, ** significant at 5% and 1% level, of significance respectively

Specific Combining Ability (SCA) Effects

The analysis of SCA effects revealed significant variation among hybrid combinations for all traits, indicating the predominance of non-additive gene action. Higher SCA effects observed in F₁ compared to F₂ suggested partial reduction of dominance effects due to segregation, although sufficient variability persisted in F₂ for selection.

For flowering traits, several crosses exhibited significant negative SCA effects, indicating desirable earliness due to favourable dominance interactions. Similarly, traits such as plant height, ear height, cob length, and kernel rows per ear

showed significant SCA effects in specific cross combinations, reflecting strong heterotic responses.

Grain yield per plant, being a complex trait, showed highly significant SCA effects in several crosses. Notably, IC 296599 × PC-4, IC 405281 × Narmada Moti, IC 569176 × Jawahar, and IC 405280 × Jawahar emerged as superior combinations, exhibiting high heterosis and favourable gene interactions. The persistence of some SCA effects in F₂ indicated that both dominance and epistatic interactions contribute to trait expression.

Table 5: SCA effects in F₁ and F₂ generations in (*Zea mays* L.)

SN	Parents/ Hybrids	Day to tassel emergence (days)		Days to silking (days)		Plant Height (cm)		No. of leaves per plant		Ear height (cm)		Cob length (cm)		No. of kernel rows / ear	
		F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁
15	IC405284 x PC-4	-0.15	1.20	0.13	0.91	0.34	-1.56	0.02	0.47	0.31	10.40 **	-0.21	-1.48 **	0.52	-0.03
16	IC 405284 x Jawahar	0.76 *	0.09	0.52	0.23	-7.46 **	-3.80 *	-0.13	-0.34	-0.90	-4.56 **	-0.09	2.10 **	-0.51	0.22
17	IC 405284 x Narmada moti	-0.61 *	-1.29 *	-0.65 *	-1.13	7.12 **	5.36 **	0.11	-0.13	0.59	-5.84 **	0.31	-0.62 *	-0.01	-0.18
18	IC 569176 x PC-4	1.58 **	-2.16 **	1.50 **	-2.23 **	2.64	0.20	0.76 **	0.50	1.67	7.29 **	-0.95 *	-0.94 **	0.39	0.43 *
19	IC 569176 x Jawahar	-1.64 **	-0.73	-1.48 **	-0.57	-4.41 **	19.69 **	-1.06 **	0.75 **	-4.25 **	9.72 **	1.10 **	0.27	0.16	-0.18
20	IC 569176 x Narmada moti	0.06	2.89 **	-0.01	2.80 **	1.77	-19.89 **	0.31	-1.24 **	2.58	-17.01 **	-0.15	0.66 *	-0.55	-0.25
21	IC408327 x PC-4	-0.68 *	-3.80 **	-0.83 **	-2.98 **	14.19 **	-4.20 *	0.93 **	-0.15	6.22 **	-3.17 *	1.66 **	0.87 **	-0.08	0.34
22	IC408327 x Jawahar	0.62 *	5.23 **	0.69 *	3.47 **	-5.93 **	8.46 **	-0.62 *	0.04	-8.17 **	2.45	-0.80 *	-0.83 **	-0.64	0.39
23	IC408327 x Narmada moti	0.06	-1.42 *	0.13	-0.49	-8.26 **	-4.26 *	-0.32	0.11	1.95	0.71	-0.86 *	-0.04	0.72	-0.74 **
24	IC 405280 x PC-4	0.89 **	1.15	0.88 **	1.00	2.57	5.11 **	-0.16	-0.10	-2.85	-5.72 **	-0.66	0.32	-0.30	-0.23
25	IC 405280 x Jawahar	-1.53 **	-1.28 *	-1.46 **	-1.02	3.77 *	-14.30 **	0.89 **	-0.79 **	10.48 **	0.65	0.29	-0.24	1.07 **	-0.12
26	IC 405280 x	0.64 *	0.13	0.58	0.02	-6.34 **	9.19 **	-0.74 **	0.89 **	-7.63	5.07 **	0.37	-0.07	-0.77	0.35

	Narmada moti									**					
27	IC 563954 x PC-4	2.18 **	3.64 **	2.15 **	3.46 **	-6.92 **	12.73 **	-1.18 **	-0.01	-6.14 **	2.43	-0.10	0.63 *	0.51	-0.14
28	IC 563954 x Jawahar	-2.18 **	-3.36 **	-2.06 **	-3.22 **	7.85 **	-4.26 *	0.81 **	0.77 **	6.13 **	4.63 **	0.14	-0.55	-0.26	0.04
29	IC 563954 x Narmada moti	-0.01	-0.28	-0.09	-0.25	-0.93	-8.47 **	0.37	-0.76 **	0.01	-7.07 **	-0.04	-0.08	-0.25	0.11
30	IC 584593 x PC-4	-0.88 **	0.62	-1.03 **	0.57	-1.48	-5.47 **	0.11	0.01	-4.08 *	-2.02	0.06	0.09	-0.08	-0.59 **
31	IC 584593 x Jawahar	-0.57	1.38 *	-0.51	1.49 *	-3.76 *	8.57 **	0.03	0.26	-1.33	-5.67 **	-0.10	0.71 *	-0.18	0.39
32	IC 584593 x Narmada moti	1.46 **	-2.00 **	1.53 **	-2.07 **	5.25 **	-3.11	-0.14	-0.27	5.42 **	7.69 **	0.04	-0.80 *	0.25	0.19
33	IC 296599 x PC-4	-1.82 **	2.66 **	-1.67 **	2.12 **	-12.67 **	-2.09	-0.89 **	-0.68 *	-1.53	-7.09 **	0.57	-0.26	-0.59	0.06
34	IC 296599 x Jawahar	3.22 **	-2.71 **	3.12 **	-1.66 **	10.60 **	-12.60 **	0.23	-0.30	1.28	-3.16 *	-0.99 **	-0.24	-0.09	-0.23
35	IC 296599 x Narmada moti	-1.41 **	0.04	-1.45 **	-0.46	2.07	14.69 **	0.66 **	0.98 **	0.25	10.25 **	0.41	0.51	0.67	0.17
36	IC 405281 x PC-4	-1.13 **	-3.31 **	-1.14 **	-2.85 **	1.34	-4.72 **	0.40	-0.04	6.40 **	-2.13	-0.37	0.77 *	-0.39	0.17
37	IC 405281 x Jawahar	1.31 **	1.38 *	1.18 **	1.27 *	-0.66	-1.77	-0.15	-0.39	-3.25 *	-4.06 **	0.45	-1.21 **	0.45	-0.52 *
38	IC 405281 x Narmada moti	-0.19	1.93 **	-0.05	1.58 *	-0.68	6.48 **	-0.25	0.42	-3.15 *	6.19 **	-0.09	0.45	-0.06	0.35
	SE(sca effects)	0.302	0.626	0.298	0.607	1.478	1.638	0.234	0.262	1.525	1.490	0.361	0.306	0.391	0.203
	SE(bet sca effects)	0.426	0.885	0.421	0.859	2.091	2.317	0.331	0.371	2.157	2.107	0.511	0.433	0.553	0.287

Table 6: SCA effects in F₁ and F₂ generations in (*Zea mays* L.)

SN	Parents/ Hybrids	No. of ears / plants		Days to maturity (days)		Biological yield / Plant (g)		Harvest index (%)		1000 kernel weight(g)		Protein content (%)		Grain yield per plant (g)	
		F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂	F ₁
15	IC405284 x PC-4	-0.07 **	0.08 **	6.61 **	0.49	25.29 **	26.61 **	4.54 **	-0.11	12.85 **	-40.10 **	-0.47 **	-0.55 *	22.90 **	11.89 **
16	IC 405284 x Jawahar	-0.030	0.10 **	-0.06	-0.62	-20.55 **	16.11 **	2.04 *	-3.46 **	44.09 **	43.01 **	-0.33 **	0.69 **	-4.83 *	-0.49
17	IC 405284 x Narmada moti	0.10 **	-0.19 **	-6.55 **	0.13	-4.73	-42.72 **	-6.58 **	3.57 **	-56.94 **	-2.91	0.80 **	-0.13	-18.06 **	-11.40 **
18	IC 569176 x PC-4	0.08 **	-0.17 **	-2.88 *	-2.67 **	-10.07 **	-7.87 **	-0.09	1.52 *	-2.59	15.63 **	0.47 **	0.40	-5.43 **	-1.41
19	IC 569176 x Jawahar	0.05 *	0.10 **	5.72 **	0.89 *	12.42 **	31.77 **	2.07 *	1.55 *	16.10 **	9.52 **	-0.08	-0.37	11.18 **	17.76 **
20	IC 569176 x Narmada moti	-0.13 **	0.07 **	-2.84 *	1.78 **	-2.34	-23.90 **	-1.99 *	-3.07 **	-13.50 **	-25.15 **	-0.39 **	-0.03	-5.75 **	-16.34 **
21	IC408327 x PC-4	-0.010	0.07 **	-0.05	0.64	6.16 *	-2.66	-3.16 **	2.02 **	-2.33	5.65 *	0.18	0.46 *	-4.51 *	1.41
22	IC408327 x Jawahar	0.07 **	-0.07 **	-1.93	-3.53 **	-4.46	21.72 **	1.97 *	3.96 **	-7.73 **	10.98 **	0.52 **	0.01	3.09	16.33 **
23	IC408327 x Narmada moti	-0.06 **	0.000	1.98	2.89 **	-1.70	-19.06 **	1.19	-5.98 **	10.07 **	-16.63 **	-0.70 **	-0.47 *	1.42	-17.75 **
24	IC 405280 x PC-4	0.17 **	-0.040	-0.67	-3.80 **	-16.82 **	-32.71 **	-0.38	-1.58 *	-31.17 **	6.96 **	-0.52 **	-0.04	-9.31 **	-17.47 **
25	IC 405280 x Jawahar	-0.09 **	-0.020	-3.95 **	1.56 **	21.90 **	17.90 **	-0.89	-3.78 **	22.82 **	-12.60 **	-0.72 **	-0.68 **	9.39 **	-1.35
26	IC 405280 x Narmada moti	-0.07 **	0.06 **	4.63 **	2.24 **	-5.08	14.80 **	1.27	5.36 **	8.35 **	5.64 *	1.23 **	0.72 **	-0.08	18.82 **
27	IC 563954 x PC-4	-0.07 **	0.030	3.26 **	-1.13 *	-4.53	0.67	1.98 *	2.76 **	-6.67 **	10.43 **	1.26 **	-0.06	1.63	5.43 **
28	IC 563954 x Jawahar	0.000	0.000	-0.62	1.22 **	-11.91 **	-21.89 **	-0.49	-3.31 **	1.13	-17.72 **	0.00	-0.56 *	-5.89 **	-16.48 **
29	IC 563954 x Narmada moti	0.08 **	-0.020	-2.64 *	-0.09	16.44 **	21.22 **	-1.49	0.55	5.54 *	7.29 **	-1.26 **	0.62 **	4.27 *	11.05 **
30	IC 584593 x PC-4	-0.06 *	0.020	1.84	4.40 **	-43.00 **	-1.22	1.20	-2.44 **	30.74 **	18.57 **	-0.29 *	0.02	-14.63 **	-5.94 **
31	IC 584593 x Jawahar	0.05 *	-0.030	-0.84	1.89 **	68.60 **	26.47 **	-6.32 **	-0.02	-33.23 **	-26.65 **	0.70 **	0.21	13.86 **	11.10 **
32	IC 584593 x Narmada moti	0.010	0.010	-1.00	-6.29 **	-25.60 **	-25.24 **	5.13 **	2.46 **	2.49	8.09 **	-0.41 **	-0.23	0.77	-5.15 **
33	IC 296599 x PC-4	-0.09 **	-0.020	-3.59 **	1.62 **	34.74 **	-14.42 **	-2.98 **	1.47 *	-0.09	1.90	-0.86 **	-0.49 *	8.37 **	1.09
34	IC 296599 x Jawahar	0.040	-0.010	-1.79	-2.89 **	-38.67 **	-63.15 **	1.23	5.63 **	-19.82 **	-10.56 **	0.10	0.56 *	-14.76 **	-12.22 **

35	IC 296599 x Narmada moti	0.05 *	0.040	5.38 **	1.26 **	3.93	77.57 **	1.75 *	-7.10 **	19.91 **	8.66 **	0.76 **	-0.07	6.38 **	11.13 **
36	IC 405281 x PC-4	0.04 *	0.030	-4.52 **	0.44	8.23 **	31.60 **	-1.10	-3.64 **	-0.72	-19.03 **	0.22	0.27	0.98	5.00 **
37	IC 405281 x Jawahar	-0.07 **	-0.07 **	3.47 **	1.47 **	-27.33 **	-28.93 **	0.38	-0.58	-23.36 **	4.01	-0.20	0.15	-12.03 **	-14.64 **
38	IC 405281 x Narmada moti	0.020	0.040	1.05	-1.91 **	19.10 **	-2.67	0.71	4.22 **	24.09 **	15.01 **	-0.03	-0.42	11.05 **	9.64 **
	SE(sca effects)	0.021	0.021	1.135	0.427	2.588	2.487	0.781	0.635	2.229	2.464	0.115	0.214	1.812	1.451
	SE(bet sca effects)	0.030	0.030	1.605	0.604	3.661	3.517	1.104	0.899	3.153	3.485	0.163	0.303	2.562	2.052

Genetic implications

The simultaneous importance of GCA and SCA effects indicates that both additive and non-additive gene actions play a crucial role in controlling yield and its components in maize. Traits governed by additive effects can be improved through selection, whereas traits influenced by non-additive gene action are better exploited through heterosis breeding. Overall, the study identified IC 296599 and IC 405281 as superior general combiners for yield, and IC 405284 and IC 569176 for earliness. Crosses such as IC 296599 × PC-4 and IC 405281 × Narmada Moti were found to be highly promising for hybrid development. These results emphasize the importance of integrating selection and hybrid breeding approaches for developing high-yielding and stable maize cultivars.

Conclusion

The study revealed significant genetic variability among maize genotypes, with both general combining ability (GCA) and specific combining ability (SCA) effects playing important roles in trait inheritance. Lines IC 296599 and IC 405281 were identified as superior general combiners for grain yield and related traits, while IC 405284 and IC 569176 were suitable for earliness. Among testers, Jawahar and PC-4 showed desirable contributions for yield and early maturity, respectively. The predominance of additive gene action for several traits suggests the effectiveness of selection, whereas significant SCA effects, particularly for grain yield, highlight the importance of heterosis breeding. Promising crosses such as IC 296599 × PC-4 and IC 405281 × Narmada Moti can be utilized for hybrid development.

Future scope and recommendations

The promising parental lines and cross combinations identified in the present study should be further evaluated across multiple locations and seasons to assess their stability and adaptability under diverse agro-climatic conditions. The superior hybrids, particularly IC 296599 × PC-4 and IC 405281 × Narmada Moti, may be advanced for large-scale testing and potential commercialization. Since both additive and non-additive gene actions were observed, a combined breeding approach involving hybrid development along with selection in segregating generations is recommended. Additionally, integration of molecular breeding tools and marker-assisted selection could enhance the efficiency of selecting superior genotypes for yield, earliness, and stress tolerance, thereby accelerating maize improvement programmes.

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