COMBINING ABILITY FOR GRAIN YIELD AND ITS CONTRIBUTING TRAITS OVER ENVIRONMENTS IN MAIZE (*ZEA MAYS* L.)

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Abstract. An investigation was carried out in maize to estimate General Combining ability (GCA), Specific Combining Ability (SCA) and their interaction with three environments. Nine maize inbred lines were crossed in all possible combinations including reciprocals in 9 × 9 diallel fashion. The resultant single cross hybrids along with parents were evaluated for their combining ability over environments. The combining ability analysis of diallel crosses across three environments showed high significance of GCA and SCA variances for all the traits viz., days to physiological maturity, plant height, cob length, cob girth, cob weight, 100 grain weight and grain yield per plant indicating the importance of both additive and non-additive gene action for the expression of these traits. The ratio of additive to non-additive variance was greater than one for all the traits except for cob length, cob girth, cob weight and grain yield across the environments, indicating the additive type of gene effects were more important in the expression days to physiological maturity, plant height and 100 grain weight and thus simple selection would confer rapid improvement of these characters. The hybrid combination UMI79 × UMI176 was the best for grain yield, cob weight, cob girth and early maturity. For reduced plant height UMI176 × UMI467 was the best across environments. The hybrid UMI176 × UMI13 was identified as the best for cob weight and cob girth. The crosses UMI79 × UMI57, UMI79 × UMI285 and UMI432 × UMI936(W) were the best for cob length.
Keywords: *gene action, inbreds, hybrids, pooled analysis, environment interaction*

Introduction

Among cereals, maize or Indian corn (*Zea mays* L.) ranks as one of the four principal crops of the world. Worldwide, corn ranks behind only wheat in total production. It has greater adaptability and is grown throughout the world, over a wide range of climatic conditions. Maize has three possible uses: food, feed for livestock and raw material for industries. Knowledge of variances of general and specific combining ability and of their interactions with different environments is useful in formulating corn breeding

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procedures. The variance for general combining ability includes the additive genetic portion while specific combining ability is usually defined as including the non-additive genetic portion of the total variance arising largely from dominance and epistatic deviations. In highly selected material the variance due to epistasis was larger than the variance of general combining ability, while in unselected material the variance of general combining ability was the larger (Sprague and Tatum, 1942).

Han et al. (1991) carried out population diallel to examine the combining ability effects of lines derived from populations and pools at the International and Maize and Wheat Improvement Center (CIMMYT) and they obtained the results which showed either good or poor general combining ability for the lines derived from the same population. This suggested that the general combining ability effect of a line is not closely associated with the populations involved in the study. However, they found positive and negative specific combining ability effects for the crosses produced by inter- and intra-population lines respectively.

Additive genetic effects were found to be more important in controlling yield of CIMMYT’s subtropical and temperate intermediate maturing germplasm (Beck et al., 1991) as well as subtropical and temperate early maturing germplasm (Vasal et al., 1992). Xingming et al. (2001) in their study with ten Quality protein maize inbreds and crosses tested in three different environments for grain yield and found highly significant difference for general combining ability while non significant difference for specific combining ability and indicated that grain yield for hybrid was mainly governed by additive gene action. Koirala and Gurung (2002) indicated the relative importance of non-additive genetic effects in controlling expression of yield in their yellow maize population.

Seventeen inbred lines and their hybrids were evaluated in twelve stress and non stress environments (Betran et al., 2003a and b) in which specific combining ability was not affected by parental inbred performance and had better prediction value for F_1 grain yield than heterosis. Combining ability analysis carried out by Dodia and Joshi (2003) showed the predominant role of non-additive type of genetic component in the inheritance of oil content, protein content, starch content, hundred grain weight and grain yield of maize. An increase in non-additive genetic effects, relative to additive genetic effects was observed in a population improvement method using recurrent selection in maize (Doerksen et al., 2003).

Materials and methods

The research work was carried out to study the combining ability effects in single cross maize hybrids at the Department of Millets, Centre for Plant Breeding and Genetics, Tamil Nadu Agricultural University, Coimbatore. The materials selected as parents for the present study consisted of nine maize inbred lines maintained by sib mating. The source and details of the parent materials are given in *Table 1*. Nine inbred lines were crossed in all possible combination including reciprocals in diallel fashion to synthesize seventy two F_1 hybrids by following tassel bag method (Jugenheimer, 1976).

Totally, seventy two hybrids along with their nine parents were raised in Randomized Blocks Design replicated thrice during three seasons (Summer, Kharif and Rabi) at the Department of Millets, Centre for Plant Breeding and Genetics, Tamil Nadu Agricultural University, Coimbatore. They were sown with inter and intra row spacing of 60 cm and 25 cm respectively. Each entry per replication was represented by a single

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row of 4 m length which can accommodate 16 plants per row. All agronomic practices recommended in Crop production manual (TNAU, 1999) were followed to grow a successful crop.

Table 1. *Details of the parent materials used in the study*

Sl. No.	Parental genotypes	Code used in the present study	Pedigree/origin
1.	UMI 79	P1	Mass Selection from Pioneer 102
2.	UMI 176	P2	Mass Selection from V46
3.	UMI 432	P3	Derivative of UMI 25 × UMI 103
4.	UMI 467	P4	Mass Selection from K1
5.	UMI 13	P5	Mass Selection from CM 111
6.	UMI 57	P6	Mass Selection from DMR pool – Taiwan-3
7.	UMI 102	P7	Mass Selection from EH 431873
8.	UMI 936 (w)	P8	Mass Selection from DMR pool – Taiwan 524
9.	UMI 285	P9	Mass Selection from Suwan 1 – Indonesia composite

The observations on days to physiological maturity (days taken from sowing to cob husk turning brown colour), plant height (cm) (measured from ground level to the base of the tassel after milk stage), cob length (cm) (measured from base to tip of the cob), cob girth (cm) (measured at the central part of the uppermost ear using vernier caliper), cob weight (g) (cob was sun dried up to 12 per cent moisture content and its weight was recorded), 100 grain weight (g) (100 randomly selected grains per cob were weighed at 12 per cent moisture content) and grain yield per plant (g) (grain obtained from uppermost cob after threshing at 12 per cent moisture content was weighed) were recorded in each entry, in each replication and in each season on five randomly selected competitive plants excluding border plants and their mean values were computed for statistical analysis. All the recorded characters were subjected to diallel analysis to estimate general and specific combining ability effects by Griffing (1956) method using the DIAL-SAS computer program (Zhang et al., 2005).

Results

The analysis of variance of pooled data for all characters over environments is presented in *Table 2*. The differences between environments were statistically significant at one per cent level for all the recorded characters. The differences among the genotypes and the interaction of genotypes with environments were significant at 1% level for all the characters. This satisfied the pre-requisite for proceeding further analysis.

Analysis of variance for combining ability over environments was carried out and the results on the estimates of variances due to general, specific and reciprocal combining abilities are presented in *Table 3*. The mean squares due to GCA, SCA and reciprocal variances for all the characters were highly significant over environments. The variance due to environment exhibited significant differences for all the characters except for cob length. The variance due to GCA × environment interaction and RCA × environment interaction was highly significant for all the characters over environments except for cob girth whereas variance due to SCA × environment interaction was significant for all

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the characters at 1% level except for cob girth which showed significant at 5% level. The ratios of GCA:SCA for days to physiological maturity, plant height, cob length, cob girth, cob weight, 100 grain weight and grain yield per plant were 6.60:1, 1.44:1, 0.85:1, 0.24:1, 0.17:1, 2.86:1 and 0.25:1 respectively over environments.

Table 2. *Pooled analysis of variance (ANOVA) for yield and yield contributing characters over three environments*

Sources	df	Days to physiological maturity	Plant height (cm)	Cob length (cm)	Cob girth (cm)	Cob weight (g)	100 grain weight (g)	Grain yield per plant (g)
Environment	2	238.82**	318793.43**	16.41**	3.11**	59338.23**	1344.80**	36231.89**
Replication	2	3.34	64.33	0.22	0.08	26.81	3.89	8.16
R × E	4	4.32*	-2.47	2.49*	0.04	11.09	0.52	20.83*
Genotypes	80	525.70**	3895.63**	23.22**	1.08**	11455.41**	120.89**	9104.53**
G × E	160	16.01**	411.96**	1.98**	0.06*	872.61**	14.13**	660.72**
Error	480	1.69	21.89	0.90	0.04	8.96	1.38	8.47

*, **Significance at 5% and 1% level, respectively

Table 3. *Pooled analysis of variance (ANOVA) for combining ability in 9 × 9 diallel set of crosses in respect of yield and yield contributing characters over environments*

Sources	df	Days to physiological maturity	Plant height (cm)	Cob length (cm)	Cob girth (cm)	Cob weight (g)	100 grain weight (g)	Grain yield per plant (g)
GCA	8	861.32**	2749.48**	11.6**	0.17**	1300.81**	144.14**	1551.70**
SCA	36	130.44**	1906.39**	13.65**	0.73**	7855.02**	50.38**	6133.78**
Reciprocal	36	67.57**	368.03**	0.96**	0.03**	341.50**	7.13**	265.49**
Environment	2	79.77**	106260.24**	5.40^{ns}	1.03*	19781.96**	448.12**	12077.35**
GCA × E	16	14.64**	306.76**	1.08**	0.02^{ns}	253.42**	5.37**	204.77**
SCA × E	72	4.40**	124.70**	0.65**	0.03*	281.42**	6.14**	223.57**
Rec × E	72	4.20**	112.40**	0.58**	0.01^{ns}	308.57**	3.14**	220.34**
Error	480	0.56	7.30	0.30	0.01	2.99	0.46	2.82
GCA/SCA		6.60:1	1.44:1	0.85:1	0.24:1	0.17:1	2.86:1	0.25:1

*, **Significance at 5% and 1% level, respectively

Days to physiological maturity

The *gca* effects for days to physiological maturity over environments ranged from -4.85 in P5 to 9.02 in P8. The highly significant negative *gca* effects were recorded by the parents P5 (-4.85), P1 (-2.35), P3 (-1.99), P2 (-1.61), P6 (-1.61) and P4 (-0.54) while P8 (9.02), P9 (2.17) and P7 (1.76) recorded highly significant positive *gca* effects over environments (*Table 4*). Totally ten and twenty six crosses out of thirty six recorded negative and positive *sca* effects for days to physiological maturity over environments. The effects varied from -2.18 in P1 × P7 to 4.63 in P3 × P5. The highly significant negative *sca* effects were recorded by the cross P1 × P7 (-2.18) followed by P5 × P7 (-1.78), P1 × P2 (-1.65), P4 × P7 (-1.65) and P2 × P3 (-1.62). The highly significant positive *sca* effects for days to physiological maturity were recorded by the cross P3 × P5 (4.63) followed by P2 × P6 (4.50), P1 × P4 (3.74), P2 × P8 (3.71) and P3 × P7 (3.63) over environments (*Table 5*). The *rca* effects of hybrids were presented in *Table 6*. The pooled data over environments showed eighteen hybrids each in negative and positive direction for days to physiological maturity with range of -6.33 (P6 × P1) to 6.78 (P9 × P3). The

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crosses P6 × P1 (-6.33), P5 × P4 (-5.89), P5 × P3 (-5.78), P5 × P2 (-4.78) and P7 × P1 (-4.44) exhibited highly significant negative *rca* effects while the crosses P9 × P3 (6.78), P9 × P5 (6.61), P2 × P1 (5.61), P7 × P3 (4.72) and P3 × P1 (3.67) exhibited highly significant positive *rca* effects for days to physiological maturity over environments (*Table 6*).

Plant height

The *gca* effects over environment ranged from -14.37 (P4) to 6.34 (P1) for plant height. The parents P4 (-14.37), P5 (-8.15) and P6 (-2.57) exhibited highly significant negative *gca* effects while the parents P1 (6.34), P9 (5.67), P7 (5.29), P3 (4.32) and P2 (2.91) exhibited highly significant positive *gca* effects over environments (*Table 4*). Seven and twenty nine hybrids registered negative and positive *sca* effects respectively over environments. It ranged from -16.30 (P2 × P4) to 23.43 (P2 × P7) over environments. The hybrids, P2 × P4 (-16.30), P2 × P3 (-8.16) and P3 × P5 (-2.75) exhibited highly significant negative *sca* effects for plant height over environments. The highly significant positive *sca* effects were recorded by the cross P2 × P7 (23.43) followed by P1 × P4 (15.74), P2 × P8 (15.31), P4 × P5 (13.41) and P7 × P9 (12.65) over environments (*Table 5*). The negative and positive *rca* effects for plant height over environments were registered by nineteen and seventeen hybrids respectively and varied from -21.86 (P2 × P1) to 16.07 (P5 × P2). The highly significant negative *rca* effects were recorded by the cross P2 × P1 (-21.86) followed by P3 × P1 (-10.68), P4 × P1 (-10.35), P7 × P4 (-9.06) and P9 × P5 (-7.67) for plant height across environments (*Table 6*).

Table 4. *Estimates of general combining ability (gca) effects of parents in 9 × 9 diallel mating design for yield and yield contributing characters over environments using Griffing's method*

Sl. No.	Entries	Days to physiological maturity	Plant height (cm)	Cob length (cm)	Cob girth (cm)	Cob weight (g)	100 grain weight (g)	Grain yield per plant (g)
	Parents							
1	P1	-2.35**	6.34**	0.36**	0.04**	8.39**	2.16**	9.57**
2	P2	-1.61**	2.91**	-0.58**	0.08**	3.65**	1.71**	3.69**
3	P3	-1.99**	4.32**	0.50**	0.05**	5.51**	0.28**	6.08**
4	P4	-0.54**	-14.37**	-0.45**	-0.01	-7.37**	-0.10	-7.61**
5	P5	-4.85**	-8.15**	-0.54**	0.03*	-1.67**	0.01	-1.82**
6	P6	-1.61**	-2.57**	0.29**	-0.09**	-1.98**	-0.14	-1.69**
7	P7	1.76**	5.29**	-0.32**	-0.01	-2.27**	-2.13**	-3.40**
8	P8	9.02**	0.55	0.54**	0.00	-0.80**	-2.83**	-2.92**
9	P9	2.17**	5.67**	0.20**	-0.08**	-3.45**	1.04**	-1.91**
SE		0.096	0.347	0.070	0.015	0.222	0.087	0.216

*, **Significance at 5% and 1% level, respectively

Cob length

The range of *gca* effects for cob length was from -0.58 (P2) to 0.54 (P8) over environments. The parents P8 (0.54), P3 (0.50), P1 (0.36), P6 (0.29) and P9 (0.20) recorded highly significant positive *gca* effects whereas the parents P2 (-0.58), P5 (-0.54), P4 (-0.45) and P7 (-0.32) registered highly significant negative *gca* effects over environments (*Table 4*). Out of thirty four and two crosses showed positive and negative *sca* effects for cob length over environments and the effects varied from -0.82 (P2 × P4) to 1.17 (P2 × P7). The highly significant positive *sca* effects were recorded by

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a cross P2 × P7 (1.17) followed by P1 × P2 (1.13), P5 × P6 (1.10), P6 × P7 (1.05) and P2 × P5 (0.97) whereas only one cross, P2 × P4 (-0.82) showed highly significant negative *sca* effects for cob length over environments (*Table 5*). The *rca* effects over environments ranged from -1.02 (P4 × P1) to 0.82 (P7 × P3) for cob length and the positive and negative *rca* effects were recorded by twenty one and fifteen hybrids respectively. The highly significant positive *rca* effects were recorded by P7 × P3 (0.82) followed by P6 × P4 (0.72) and P4 × P3 (0.69) and the highly significant negative *rca* effects were recorded by P4 × P1 (-1.02) followed by P3 × P1 (-0.88) and P9 × P6 (-0.61) for cob length across environments (*Table 6*).

Table 5. *Estimates of specific combining ability (sca) effects of hybrids in 9 × 9 diallel set of crosses for yield and yield contributing characters over environments using Griffing's method*

Sl. No.	Entries	Days to physiological maturity	Plant height (cm)	Cob length (cm)	Cob girth (cm)	Cob weight (g)	100 grain weight (g)	Grain yield per plant (g)
	Direct crosses							
1	P1 × P2	-1.65**	1.17	1.13**	0.26**	27.55**	2.30**	26.38**
2	P1 × P3	1.35**	9.21**	0.00	0.04	13.93**	-0.12	14.28**
3	P1 × P4	3.74**	15.74**	0.39	0.07	5.98**	2.80**	5.97**
4	P1 × P5	-0.12	3.47**	0.80**	0.08	4.68**	0.86**	7.67**
5	P1 × P6	2.96**	-0.65	0.69**	0.18**	17.27**	1.73**	13.62**
6	P1 × P7	-2.18**	2.44*	0.07	0.12**	11.11**	-0.93**	7.49**
7	P1 × P8	3.45**	11.89**	0.00	0.19**	9.28**	1.83**	7.85**
8	P1 × P9	1.19**	4.79**	0.66**	-0.01	10.55**	1.06**	8.92**
9	P2 × P3	-1.62**	-8.16**	0.16	0.17**	11.08**	1.43**	9.56**
10	P2 × P4	1.94**	-16.30**	-0.82**	0.22**	-3.68**	0.85**	-3.33**
11	P2 × P5	0.47	2.07*	0.97**	0.15**	19.93**	0.38	17.18**
12	P2 × P6	4.50**	8.69**	0.40*	0.04	4.79**	0.82**	4.33**
13	P2 × P7	0.36	23.43**	1.17**	0.00	14.27**	1.54**	13.00**
14	P2 × P8	3.71**	15.31**	0.66**	0.00	12.08**	1.01**	9.41**
15	P2 × P9	1.06**	10.41**	0.77**	0.12**	15.20**	0.95**	15.19**
16	P3 × P4	2.54**	1.87	0.14	0.05	2.61**	-1.12**	1.22*
17	P3 × P5	4.63**	-2.75**	0.15	0.07	4.70**	0.78**	4.43**
18	P3 × P6	-0.06	2.74**	0.15	0.01	4.94**	0.98**	7.68**
19	P3 × P7	3.63**	-0.71	0.04	0.15**	13.28**	-0.34	10.01**
20	P3 × P8	3.15**	5.34**	0.57**	-0.04	7.79**	0.36	7.96**
21	P3 × P9	-0.17	-1.10	0.11	0.09*	10.21**	0.97**	10.08**
22	P4 × P5	1.63**	13.41**	0.59**	0.18**	18.14**	1.25**	12.28**
23	P4 × P6	2.11**	6.17**	-0.02	0.09*	14.21**	0.94**	12.08**
24	P4 × P7	-1.65**	-0.46	0.92**	0.04	17.06**	1.38**	15.33**
25	P4 × P8	1.37**	2.57**	0.12	0.17**	16.21**	0.94**	13.12**
26	P4 × P9	-0.45	6.42**	0.47*	0.08	12.29**	0.97**	11.58**
27	P5 × P6	1.03**	11.67**	1.10**	0.11*	13.83**	-0.49*	9.46**
28	P5 × P7	-1.78**	8.59**	0.53**	0.15**	10.03**	1.42**	12.15**
29	P5 × P8	3.01**	2.09*	0.68**	0.09*	15.01**	1.65**	9.74**
30	P5 × P9	1.97**	1.96*	0.58**	0.15**	16.88**	1.21**	13.82**
31	P6 × P7	1.25**	4.34**	1.05**	0.27**	21.04**	2.80**	19.72**
32	P6 × P8	3.43**	11.32**	0.66**	0.08	10.44**	-0.01	10.10**
33	P6 × P9	0.11	4.28**	0.48*	0.10*	15.00**	0.53*	12.63**
34	P7 × P8	0.18	7.24**	0.41*	0.15**	9.09**	0.57*	9.08**
35	P7 × P9	2.58**	12.65**	0.36	0.10*	1.10	-0.67*	-0.14
36	P8 × P9	-0.07	4.27**	0.48*	0.32**	17.64**	1.47**	16.21**
	SE	0.275	0.988	0.200	0.043	0.632	0.248	0.614

*, **Significance at 5% and 1% level, respectively

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Table 6. *Estimates of rca effects of hybrids in 9 × 9 diallel set of crosses for yield and yield contributing characters over environments using Griffing's method*

Sl. No.	Entries	Days to physiological maturity	Plant height (cm)	Cob length (cm)	Cob girth (cm)	Cob weight (g)	100 grain weight (g)	Grain yield per plant (g)
	Reciprocals							
37	P2 × P1	5.61**	-21.86**	-0.26	0.00	3.20**	-0.01	3.96**
38	P3 × P1	3.67**	-10.68**	-0.88**	-0.05	-11.01**	-1.23**	-10.86**
39	P3 × P2	-3.89**	-3.24**	-0.29	-0.01	-5.68**	2.54**	-4.17**
40	P4 × P1	-1.61**	-10.35**	-1.02**	-0.07	-13.84**	-1.89**	-12.40**
41	P4 × P2	0.78*	-5.52**	-0.12	-0.01	-3.63**	-0.67*	-0.08
42	P4 × P3	0.56	7.14**	0.69**	0.01	1.93**	0.09	4.19**
43	P5 × P1	-1.22**	10.38**	0.17	0.06	12.78**	1.21**	10.91**
44	P5 × P2	-4.78**	16.07**	0.26	0.13**	18.37**	1.56**	14.30**
45	P5 × P3	-5.78**	3.68**	0.56*	0.09	7.27**	0.41	4.32**
46	P5 × P4	-5.89**	3.23**	0.27	-0.06	1.29	-0.77**	2.46**
47	P6 × P1	-6.33**	7.64**	0.27	0.02	-7.96**	0.61*	-5.53**
48	P6 × P2	-3.17**	-1.96	-0.14	0.00	-3.42**	-0.21	-6.19**
49	P6 × P3	2.11**	-1.64	-0.03	0.03	0.67	-0.37	1.43*
50	P6 × P4	-0.17	3.98**	0.72**	0.05	17.64**	0.64*	15.87**
51	P6 × P5	1.00**	4.94**	-0.30	0.10*	7.56**	0.97**	6.93**
52	P7 × P1	-4.44**	-10.13**	0.22	0.15**	8.34**	0.38	9.14**
53	P7 × P2	3.61**	8.98**	0.18	0.08	8.95**	2.28**	7.36**
54	P7 × P3	4.72**	4.81**	0.82**	0.03	4.79**	-0.09	5.98**
55	P7 × P4	1.44**	-9.06**	0.46*	0.04	7.53**	-0.35	5.07**
56	P7 × P5	1.44**	-7.01**	-0.19	-0.02	5.36**	-1.14**	4.18**
57	P7 × P6	-0.50	2.90**	0.18	0.04	8.25**	-1.26**	5.16**
58	P8 × P1	-0.56	-2.34*	0.03	0.06	9.11**	1.17**	7.57**
59	P8 × P2	1.00**	8.30**	-0.11	-0.09	6.68**	1.46**	6.08**
60	P8 × P3	1.94**	-3.19**	0.06	-0.05	-5.02**	-1.56**	-6.04**
61	P8 × P4	1.61**	1.61	0.19	0.16**	1.53*	0.88**	-1.25
62	P8 × P5	-0.61*	-5.46**	0.21	0.01	2.52**	0.62*	-0.10
63	P8 × P6	0.39	-2.30*	-0.22	-0.02	-1.36	-0.79**	-0.18
64	P8 × P7	-0.39	3.74**	0.17	-0.04	-3.13**	-0.33	-1.77**
65	P9 × P1	-4.11**	9.78**	0.09	0.09	5.48**	2.22**	5.73**
66	P9 × P2	-2.39**	-0.27	-0.30	0.09	1.52*	0.74**	1.72*
67	P9 × P3	6.78**	-3.86**	0.13	-0.04	-4.45**	-0.88**	-7.38**
68	P9 × P4	3.50**	-5.21**	0.39	0.10*	3.32**	0.32	3.63**
69	P9 × P5	6.61**	-7.67**	-0.52*	0.10*	-2.69**	0.73**	-3.66**
70	P9 × P6	-0.11	2.21*	-0.61**	0.01	3.75**	-0.54	-0.78
71	P9 × P7	0.50	14.76**	-0.13	0.08	9.56**	0.22	7.14**
72	P9 × P8	-1.11**	-4.59**	0.05	-0.10*	1.57*	0.87**	2.04**
	SE	0.307	1.103	0.223	0.048	0.705	0.277	0.686

*, **Significance at 5% and 1% level, respectively

Cob girth

The range of *gca* effects for cob girth over environments was from -0.09 in P6 to 0.08 in P2. The parents P2 (0.08), P3 (0.05) and P1 (0.04) recorded highly significant positive *gca* effects while the parents P6 (-0.09) and P9 (-0.08) recorded highly significant negative *gca* effects for cob length over environments (*Table 4*). Out of thirty six direct crosses, thirty four and two crosses recorded positive and negative *sca*

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effects respectively over environments. The *sca* effects for cob girth varied from -0.04 (P3 × P8) to 0.32 (P8 × P9). The highly significant positive *sca* effects were recorded by the cross P8 × P9 (0.32) followed by P6 × P7 (0.27), P1 × P2 (0.26), P2 × P4 (0.22) and P1 × P8 (0.19) whereas none of the crosses showed significant negative *sca* effects for cob girth over environments (*Table 5*). Totally twenty one reciprocal hybrids recorded positive *rca* effects while rest of them showed negative *rca* effects for cob girth across environments and varied from -0.10 (P9 × P8) to 0.16 (P8 × P4). The highly significant positive *rca* effects were recorded by the hybrids P8 × P4 (0.16) followed by P7 × P1 (0.15) and P5 × P2 (0.13) whereas P9 × P8 recorded significant negative *rca* effects for cob girth over environments (*Table 6*).

Cob weight

The *gca* effects for cob weight over environments varied from -7.37 (P4) to 8.39 (P1). The highly significant positive *gca* effects were exhibited by the parents P1 (8.39), P3 (5.51) and P2 (3.65). The parents P4 (-7.37), P9 (-3.45), P7 (-2.27), P6 (-1.98), P5 (-1.67) and P8 (-0.80) recorded highly significant negative *gca* effects for cob weight over environments (*Table 4*). Among direct crosses positive and negative *sca* effects were recorded by thirty five and one hybrids respectively for cob weight over environments. It varied from -3.68 (P2 × P7) to 27.55 (P1 × P2). The highly significant positive *sca* effects for cob weight were recorded by the cross P1 × P2 (27.55) followed by P6 × P7 (21.04), P2 × P5 (19.93), P4 × P5 (18.14) and P1 × P (17.27) whereas only one hybrid showed highly significant negative *sca* effects for cob weight over environments (*Table 5*). The positive and negative *rca* effects were registered by twenty five and eleven hybrids respectively for cob weight across environments and ranged from -13.84 (P4 × P1) to 18.37 (P5 × P2). A highly significant positive *rca* effects were recorded by the cross P5 × P2 (18.37) followed by P6 × P4 (17.64), P5 × P1 (12.78), P9 × P7 (9.56) and P8 × P1 (9.11) and highly negative *rca* effects were recorded by P4 × P1 (-13.84) followed by P3 × P1 (-11.01), P6 × P1 (-7.96), P3 × P2 (-5.68) and P8 × P3 (-5.02) for cob weight over environments (*Table 6*).

100 grain weight

The parents P1 (2.16), P2 (1.71), P9 (1.04) and P3 (0.28) recorded highly significant positive *gca* effects for 100 grain weight whereas P8 (-2.83) and P7 (-2.13) recorded highly significant negative *gca* effects over environments for 100 grain weight (*Table 4*). Totally twenty nine and seven hybrids recorded positive and negative *sca* effects for 100 grain weight across environments and ranged from -1.12 (P3 × P4) to 2.80 (P1 × P4). The highly significant positive *sca* effects were recorded by the hybrids P1 × P4 (2.80) followed by P6 × P7 (2.80), P1 × P2 (2.30), P1 × P8 (1.83) and P1 × P6 (1.73) and the highly significant negative *sca* effects were recorded by two hybrids namely, P3 × P4 (-1.12) and P1 × P7 (-0.93) (*Table 5*). Totally twenty reciprocal hybrids out of thirty six, showed positive *rca* effects for 100 grain weight over environments while rest of them showed negative values. The *rca* effects varied from -1.89 in P4 × P1 to 22.54 in P3 × P2. A highly significant positive *rca* effects were recorded by the cross P3 × P2 (2.54) followed by P7 × P2 (2.28), P9 × P1 (2.22), P5 × P2 (1.56) and P8 × P2 (1.46) and highly significant negative *rca* effects were recorded by P4 × P1 (-1.89) followed by P8 × P3 (-1.56), P7 × P6 (-1.26), P3 × P1 (-1.23) and P7 × P5 (-1.14) for 100 grain weight across environments (*Table 6*).

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Grain yield per plant

The estimates of *gca* effects over environments varied from -7.61 (P4) to 9.57 (P1) for grain yield per plant. The highly significant positive *gca* effects were registered by the parent P1 (9.57) followed by P3 (6.08) and P2 (3.69) and the highly significant negative *gca* effects were registered by the parent P4 (-7.61) followed by P7 (-3.40), P8 (-2.92), P9 (-1.91), P5 (-1.82) and P6 (-1.69) for grain yield per plant over environments (*Table 4*). Thirty four and two hybrids showed positive and negative *sca* effects respectively over environments and ranged from -3.33 (P2 × P4) to 26.38 (P1 × P2). The highly significant positive *sca* effects were recorded by the cross P1 × P2 (26.38) followed by P6 × P7 (19.72), P2 × P5 (17.18), P8 × P9 (116.21) and P2 × P9 (15.19). Only one cross showed highly significant negative *sca* effects for seed weight over environments (*Table 5*). Out of thirty six reciprocal crosses twenty two and fourteen hybrids showed positive and negative *rca* effects for seed weight over environments. It ranged from -12.40 in P4 × P1 to 15.87 in P6 × P4. The crosses P6 × P4 (15.87), P5 × P2 (14.30), P5 × P1 (10.91), P7 × P1 (9.14) and P8 × P1 (7.57) recorded highly significant positive *rca* effects while the crosses P4 × P1 (-12.40), P3 × P1 (-10.86), P9 × P3 (-7.38), P6 × P2 (-6.19) and P8 × P3 (-6.04) recorded highly significant negative *rca* effects for grain yield across environments (*Table 6*).

Discussion

The combining ability analysis is an important tool in the hands of breeders to identify good lines in their breeding material and further to select promising hybrid combinations to develop suitable hybrids from them. The nature and magnitude of gene action helps in finalizing the breeding strategies. In the present study, combining ability analysis was carried out to understand the gene action governing the characters over three environments.

Pooled analysis of variance over environments showed highly significant variation among the genotype for all the characters studied, suggesting enough genetic diversity among the genotypes for these characters. Significant differences between environments, genotypes, genotype × environment interactions were detected in the combined analysis which suggested that the genotypes did not have the same relative performance across environments and they interacted significantly with all environments for all the characters. Therefore, it indicates the importance of both genotype and environmental components in determining the expression of these traits.

The combining ability analysis of diallel data across environments showed the highly significance GCA and SCA variances for all the traits over environments indicating the importance of both additive and non-additive gene action for the expression of these traits. The mean squares due to environments were significant for all the characters except cob length in pooled analysis, indicating differences among environments for the expression of days to physiological maturity, plant height, cob girth, cob weight, 100 grain weight and grain yield per plant. Significance of GCA and GCA × environment effects except for cob girth suggested the need of selecting different parental lines for hybrids at specific environments for these characters. SCA and SCA × environment interaction effects were significant for all the characters over environments indicating that the hybrids are more vulnerable to environmental fluctuation. Similar results were obtained by Rojas and Sprague (1952), Matzinger et al. (1959), Paroda and Hayes (1971), Nelson and Scott (1973) Qi et al., 2010; Alamerew and Warsi (2015) and Onejeme et al. (2020).

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Breeders use the ratio of GCA:SCA variance in order to rank the characters possessing relatively more fixable additive variation, which will largely help the breeders to exercise selection in the succeeding generation based on one or more traits. The ratio of additive to non-additive variance was greater than one for all the traits except for cob length, cob girth and cob weight across the environments, indicating the additive type of gene effects were more important in the expression of days to physiological maturity, plant height and 100 grain weight and thus simple selection would confer rapid improvement of these characters. Non-additive type of gene effects were more important for cob length, cob girth, cob weight and grain yield per plant and selection for these traits could be delayed to later generations until the non-additive portion had mitigated to additive portion as these characters showed higher magnitude of SCA variance and GCA variance over environments. In the present study, variances due to reciprocal effects were highly significant for all the characters. Hence, it is suggested that reciprocal crosses should be included in the evaluation of single cross hybrids. The reciprocal combining ability variance (RCA) × environment interaction component was significant for all the characters except for cob girth, suggesting the significant interaction of maternal factors with environments for the expression of these characters over environments.

Days to physiological maturity

Early maturing hybrids are suitable for multiple cropping while late maturing hybrids are needed in other areas to take advantage of extremely long growing seasons. For this trait both GCA and SCA variances were highly significant for combined data. The estimates of mean squares due to GCA were higher than those due to SCA, indicating the predominance of additive genetic effects for this trait. Recurrent selection for *gca*, therefore, may be the best suitable breeding methodology for developing better genotypes in these materials. Murthy et al. (1981), Satyanarayana (1996) and Gautam (2003) also reported additive gene action for days to maturity. However, Singh et al. (1979) and Sanghi et al. (1983) reported both additive and non-additive genetic variance for days to physiological maturity. Even though interaction components with environments were significant for both GCA and SCA, this study revealed that GCA was much influenced by environments than SCA for maturity character. Parents with high negative *gca* effects for maturity could be considered as the best for exploiting earliness in hybrids. Among the parents P5 was good general combiner for earliness across environments followed P1, P3, P2 and P6. These parents also had good *gca* effects in all the three environments for maturity. These parents may be used for production of early maturing synthetics and composites. The following crosses *viz,* P1 × P7, P2 × P3, P5 × P2, P5 × P3, P5 × P4, P6 × P1, P6 × P2 and P7 × P1 showed highly significant negative *sca* effects to days to physiological maturity over environments and in all the individual environments and represented parental combination of best × best and best × poor combiners. Involvement of one poor combiner in these crosses having high *sca* effects indicated that some complementary gene interaction is responsible for early maturity.

Plant height

Significant differences due to GCA and SCA for plant height indicated that both additive and non-additive genetic variation was influencing the inheritance of this trait. However, it was seen that GCA variance was higher than SCA variance for plant height

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indicating additive gene action was predominant than the non-additive component in the material under study. Similar results have been obtained by Crossa et al. (1990a), Spaner et al. (1996), Satyanarayana (1996), Geetha (2001), Xingming et al. (2001) and Gautam (2003). Additive gene action was reported for the inheritance of plant height by Singh et al. (1979), Muthiah (1989), Crossa et al. (1990b), Satyanarayana et al. (1990), Nagda et al. (1995) and Geetha and Jayaraman (2000). Both additive and non-additive gene action were obtained by Singh and Asnani (1979), Sharma et al. (1982) and Sinha and Mishra (1997). Environmental interaction with combining ability was found to be significant, which indicated the significant influence of environment in the expression of combining ability for plant height. Reduced plant height was considered to be desirable attribute in most of the maize breeding programs because of better lodging resistance (Johnson et al., 1978). Parents P4 and P5 showed highly significant negative *gca* effects across environments and also in all the three environments for plant height indicating that these parents contributed reduced plant height in their crosses. These two inbreds can be used to improve the plant performance through recurrent selection for *gca*. The crosses showing high significant negative *sca* effects over environments and in all the three environments were P2 × P4, P2 × P1, P3 × P1 and P4 × P1. These specific single crosses may be further utilized for the development of superior hybrid composites for reduced plant height.

Cob length

The mean squares due to both GCA and SCA were significant for cob length across environments. However, the ratio of additive: non-additive variance was less than one for cob length across the environments indicating the predominance of non-additive type of gene effects in controlling this and amenability of the study material for heterotic exploitation. The findings of many workers *viz.,* Muthiah (1989), Satyanarayana et al. (1990), Paul and Duara (1990) and Kalla et al. (2001) confirm this observation. However, predominance of additive gene action was reported for the inheritance of cob length by Sharma et al. (1982), Satyanarayana (1996) and Gautam (2003). The role of both additive and non-additive genetic components was observed by Singh et al. (1979), Singh and Asnani (1979), Debnath and Sarkar (1990), Sinha and Mishra (1997) and Kalla et al. (2001). Both GCA and SCA variances were highly influenced by environmental factors for cob length. The parents P3 and P8 were good general combiners across environments and in all the three individual environments and they transmitted higher cob length to its hybrids. Hybrid combinations P2 × P5, P2 × P7, P2 × P9, P5 × P6 and P6 × P7 recorded high *sca/rca* effects for cob length across environments in addition to three individual environments. But all these good specific combiners did not have good general combiners in their crosses.

Cob girth

Pooled analysis of variance revealed that both GCA and SCA variances were significant, which indicated that both GCA and SCA were important in the expression of cob girth. However, the greater magnitude of SCA variance reveals the non-additive gene action was dominant in determining cob girth for hybrids. Supportive evidences for the influence of non-additive genetic component were recorded by Muthiah (1989), Satyanarayana et al. (1990) and Satyanarayana (1996), whereas Additive gene action was reported by Alika (1994). However, the importance of both additive and non-additive gene action was indicated by Singh and Asnani (1979), Sharma et al. (1982),

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Debnath and Sarkar (1990), Sinha and Mishra (1997) and Kalla et al. (2001). The study revealed that GCA was not influenced by environments for cob girth whereas the expression of non-additive effect was influenced by diverse environments. Among parents, P1, P2, P3 and P5 were found to record good general combining ability effects for cob girth across environments and could be utilized in hybridization programme to improve cob girth. The best specific combiner with significant positive *sca* effects identified for cob girth were P1 × P8, P2 × P3, P2 × P4, P6 × P7 and P8 × P9 and are suitable for exploitation of cob girth in the hybrid.

Cob weight

In the present study, both GCA and SCA variances were observed to play an important role in the inheritance of cob weight, however, non-additive effects appeared to be more important in controlling cob weight. These results were in conformity with Satyanarayana et al. (1990), Reddy and Agarwal (1992), Geetha and Jayaraman (2000) and Kalla et al. (2001). However, Alika (1994), Geetha (2001) and Nass et al. (2000) reported additive gene action. Both additive and non-additive gene action was reported by Paul and Duara (1990) in the inheritance of cob weight in maize. Both GCA and SCA components showed interaction with changing environments. The parents P1 and P3 were found to be the best general combiners for cob weight across environments and also in all the three individual environments. The best single crosses on the basis of *sca/rca* effects for cob weight were P1 × P2, P1 × P7, P2 × P3, P2 × P5, P2 × P8, P2 × P9, P3 × P7, P3 × P9, P4 × P5, P4 × P6, P4 × P7, P4 × P8, P5 × P6, P5 × P8, P5 × P9, P6 × P7, P6 × P8, P6 × P9, P8 × P9, P5 × P1, P5 × P2, P7 × P1, P7 × P2, P7 × P5 and P9 × P7. These crosses were the best combiners for cob weight across environments and also in all the three individual environments.

100 grain weight

The combined analysis of variance over environments indicated that the variance for both GCA and SCA were significant for 100 grain weight revealing the role of both additive and non-additive gene effects. However higher influence of additive gene effects was realized than non-additive gene action for its higher GCA variance. Additive gene action for 100 grain weight was reported by Nevado et al. (1989), Alika (1994), Geetha (2001) and Xingming et al. (2001) where as non-additive gene action was inferred by Yong (1982), Debnath and Sarkar (1990), Beck et al. (1990), Crossa et al. (1990b), Satyanarayana et al. (1990), Paul and Duara (1990), Pal and Prodhan (1994), Satyanarayana (1996), Geetha and Jayaraman (2000), Kalla et al. (2001), Dodiya and Joshi (2003) and Gautam (2003). Singh et al. (1979) and Singh and Asnani (1979) reported the importance of both additive and non-additive type of gene action in controlling 100 grain weight in maize. This study revealed that both GCA and SCA variances were influenced by diverse environments. The parents P1, P2 and P9 were good general combiners for 100 grain weight across environments and also in all three individual environments. These three inbreds can be used to breed for larger kernel size. The crosses *viz.*, P1 × P4, P2 × P3, P5 × P8 and P7 × P2 recorded highly significant positive *sca* effects over environments in addition to three individual environments. These four crosses with high *sca* effects represented parental combination of average × poor and best × poor general combiners indicating the complementary nature of gene interaction for 100 grain weight in maize.

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Grain yield per plant

Analysis of variance for combining ability over environments revealed that both GCA and SCA were significantly different for grain yield which indicated the effect of both additive and non-additive gene action in the inheritance of grain yield. However, the role of non-additive gene action was inferred from its higher SCA variance than GCA. Non-additive type of gene action was reported by Murthy et al. (1981), Satyanarayana (1996), Geetha and Jayaraman (2000) and Gautam (2003). Additive type of gene action was observed for grain yield by Sanghi et al. (1983), Muthiah (1989) and Geetha (2001). The importance of both additive and non-additive genetic variance was reported by Singh et al. (1979), Singh and Asnani (1979), Sharma et al. (1982), Sanghi et al. (1983), Debnath and Sarkar (1990), Nagda et al. (1995b), Sinha and Mishra (1997) and Murtadha et al. (2018). The interaction of environment with both GCA and SCA variances was significant across environments. This suggests that it is necessary to select parental lines and hybrids in specific environments and indicated that the GCA and SCA values were not the same for all the environments. Therefore, selection for a specific environment should be carried out to improve this trait. Pooled analysis showed that the lines P1 and P3 were good general combiners for grain yield across environments and also in all the three environments and they contributed maximum number of favorable genes for grain yield in their crosses. Thus, these lines may be used for production of synthetics and composites with higher grain yield. The lines showing high *gca* effects for grain yield had high mean values. Thus, association between *per se* performance and *gca* effects was evident in the present study indicating the effectiveness of choice of parents based on *per se* performance alone for predicting combining ability of parents. The highly significant positive combining ability effects for grain yield per plant were recorded in many crosses *viz.*, P1 × P2, P1 × P3, P1 × P4, P1 × P5, P1 × P6, P1 × P7, P1 × P8, P1 × P9, P2 × P3, P2 × P5, P2 × P6, P2 × P7, P2 × P8, P2 × P9, P3 × P5, P3 × P6, P3 × P7, P3 × P8, P3 × P9, P4 × P5, P4 × P6, P4 × P7, P4 × P8, P4 × P9, P5 × P6, P5 × P7, P5 × P8, P5 × P9, P6 × P7, P6 × P8, P6 × P9, P7 × P8, P8 × P9, P2 × P1, P4 × P3, P5 × P1, P5 × P2, P5 × P3, P5 × P4, P6 × P4, P6 × P5, P7 × P1, P7 × P2, P7 × P3, P7 × P4, P7 × P5, P7 × P6, P8 × P1, P8 × P2, P9 × P1, P9 × P4, P9 × P7, P9 × P8. The hybrids involved all the types of parental combinations *viz.*, best × best, best × poor and poor × poor general combiners. The involvement of poor combiner indicates the presence of complementary gene interaction for grain yield in maize.

Conclusion

The combining ability analysis of diallel data across environments showed the highly significance GCA and SCA variances for all the traits over environments indicating the importance of both additive and non-additive gene action for the expression of these traits. The highly significant positive combining ability effects were observed in many crosses which involved parental combinations of best × best, best × poor and poor × poor general combiners indicates the presence of complementary gene action for grain yield in maize. The hybrid combination namely UMI79 × UMI176 was the best for grain yield, cob weight, cob girth and early maturity over three environments which could be used as single cross commercial hybrid.

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